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REVERSE OSMOSIS RENOVATION OF MUNICIPAL WASTEWATER

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1 Accession Number
W71-04669

2 Subject Field & Group
05D, 03A

SELECTED WATER RESOURCES ABSTRACTS
INPUT TRANSACTION FORM

5 Organization
Aerojet-General Corporation, Systems El Monte, Calif~~ornia~~
Environmental Div.

6 Title
I67.13/4:17040EPQ12/69
all copies
Reverse Osmosis Renovation of Municipal Wastewater,

Copy available from GPO Sup Doc as , $1.50; microfiche from NTIS as PB 197659, $0.95.

10 Author(s)
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16 Project Designation
FWQA Program 17040 EFQ. ~~Contract#14-12-184~~

21 Note
~~Available from the National Technical Information Service as PB , $3.00 in paper copy, $0.95 in microfiche~~

22 Citation
Water Pollution Control Research Series ORD-17040EFQ12/69, (1969). 160p, 12 tab, 107 fig,

23 Descriptors (Starred First)
*Reverse osmosis, *sewage treatment, ~~process model,~~ tertiary treatment, computer models, *membrane processes, ~~wastewater renovation,~~ demineralization, ~~solids removal, organics removal,~~ *Osmosis, *Waste water treatment, Municipal water, Solid wastes, Organic wastes,

25 Identifiers (Starred First)
Process models, *Municipal wastewater, Solids removal, Organics removal,

27 Abstract

A fifteen-month laboratory program has shown that all grades of municipal wastewater may be significantly improved by the reverse osmosis process. Comparisons are provided on the behavior and response of the reverse osmosis process to carbon-treated secondary sewage, alum-treated secondary sewage, secondary sewage, primary settled sewage, raw sewage, and digester supernatant. High removals of dissolved minerals, organic substances, and suspended matter have all been achieved in the same treatment. The effects of a flocculant, dispersant, chelating agent, enzyme, and acid on reducing product water flux decline are compared. The relative effects of reverse osmosis test-cell geometry on solids deposition and membrane performance are presented. A phenomenological model is postulated describing the role of undissolved solids and organic substances in producing product water flux decline and the subsequent maintenance of constant product water fluxes. A computer model of the reverse osmosis process, compatible with the executive program written by the Federal Water Quality Administration, has been developed to provide an accurate and rapid method of determining the design and cost of reverse osmosis facilities. (Feurstein - Aerojet-General)

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WR:102 (REV. JULY 1969)
WRSIC

SEND TO: WATER RESOURCES SCIENTIFIC INFORMATION CENTER
U.S. DEPARTMENT OF THE INTERIOR
WASHINGTON, D. C. 20240

* U. S. GOVERNMENT PRINTING OFFICE : 1970 O - 410-161

REVERSE OSMOSIS RENOVATION OF MUNICIPAL WASTEWATER

by

Environmental Systems Division
Aerojet-General Corporation
El Monte, California 91734

for the

FEDERAL WATER QUALITY ADMINISTRATION

DEPARTMENT OF THE INTERIOR

Program #17040 EFQ
Contract #14-12-184
FWQA Project Officer, G. Stern
Advanced Waste Treatment Research Laboratory
Cincinnati, Ohio

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington, D.C. 20402 - Price $1.50

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ABSTRACT

A fifteen-month laboratory program has shown that all grades of municipal wastewater may be significantly improved by the reverse osmosis process.

Comparisons are provided on the behavior and response of the reverse osmosis process to carbon-treated secondary sewage, alum-treated secondary sewage, secondary sewage, alum-treated primary sewage, primary sewage, raw sewage, and digester supernatant. High removals of dissolved minerals, organic substances, and suspended matter have all been achieved in the same treatment.

The effects of a flocculant, dispersant, chelating agent, enzyme, and acid on reducing product water flux decline are compared. The relative effects of reverse osmosis test-cell geometry on solids deposition and membrane performance are presented.

A phenomenological model is postulated describing the role of undissolved solids and organic substances in producing product water flux decline and the subsequent maintenance of constant product water fluxes.

A computer model of the reverse osmosis process, compatible with the executive program written by the Federal Water Quality Administration, has been developed to provide an accurate and rapid method of determining the design and cost of reverse osmosis facilities.

This report was submitted in fulfillment of Program No. 17040 EFQ and Contract No. 14-12-184 between the Federal Water Quality Administration and the Aerojet-General Corporation.

Key Words: Reverse osmosis, sewage treatment, process model, tertiary treatment, computer model, membrane process, wastewater renovation, demineralization, solids removal, organics removal.

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CONCLUSIONS AND RECOMMENDATIONS

Based on the conduct of nearly 90 individual laboratory-scale reverse osmosis tests to determine the effects of municipal wastewater quality and operating conditions on process performance, a number of conclusions are presented.

The product water flux approached within 20 days from commencement of operations a relatively constant value for all of the municipal wastewaters tested for at least that period of time. The level of stabilized product water flux was directly related, within certain limits, to membrane permeability and feed water quality. For a fixed set of operating conditions, membrane material, annealing temperature and no preconditioning other than pH adjustment, the same product water flux of 2 gal/(sq ft)(day) was obtained with raw sewage and primary sewage, but increased progressively to 6 gal/(sq ft)(day) with secondary sewage and to greater than 18 gal/(sq ft)(day) with carbon-treated secondary sewage. Whereas a stabilized product water flux of 5. 5 gal/(sq ft)(day) was obtained with the standard membrane material (degree of acetyl substitution, 2. 41) on alum-treated, sand-filtered primary settled sewage, a higher stabilized product water flux of 17 gal/(sq ft)(day) was obtained on the same feed water under identical operating conditions with an advanced membrane (degree of acetyl substitution, 2. 64) possessing an inherently greater product water flux capability. Thus it would appear that the deposited material on the membrane is not the only limiting factor in achieving maximum product water flux, indicating that higher purified water production can be expected from the processing of properly conditioned municipal wastewater with reverse osmosis membranes having intrinsicly greater water transport properties.

High removals of most major pollutants contained in municipal wastewater were accomplished by the reverse osmosis process. Although the rejections were dependent somewhat upon the feed water quality and the operating conditions, average removals for a 68° flat-plate membrane, excluding digester supernatant, ranged from 83 to 92 percent for total dissolved salts as measured by electrical conductivity (EC), from 79 to 94 for oxidizable organics (COD), from 71 to 92 for organic nitrogen, from 74 to 87 percent for ammonium, from 45 to 90 percent for nitrite, from 23 to 92 percent for nitrate, from 93 to 99 percent for phosphate, and from 83 to 99 percent for methylene blue active substances (MBAS).

A continuous extended test of 2. 5-month duration demonstrated that a constant product water flux of about 5. 5 gal/(sq ft)(day) could be maintained with alum-treated, sand-filtered primary settled sewage at product water recovery ratios as high as 95 percent.

Continuous tests using an advanced cellulose acetate-cellulose triacetate blend membrane produced a product water flux of around 17 gal/(sq ft)(day) with alum-treated, sand-filtered primary settled sewage during a scheduled 12-day test period.

Of the three types of additives studied, the flocculating agents were more effective than either a dispersant or chelating agent in reducing the product water flux decline and in producing the highest stabilized product water flux, when used in the concentrations chosen. Pretreatment of the municipal wastewater feed by flocculation with aluminum sulfate (alum) followed by rapid sand filtration was the best of all preconditioning methods used for maintaining product water flux at the highest levels. It appears however that similar results may be experienced with organic flocculating agents.

The principal causative agent in the membrane fouling process appears to be finely dispersed solids. Dissolved organic substances are of lesser relative importance; whereas the effect of gross readily settleable matter is negligible.

Development of a constant product water flux is believed to be the consequence of an equilibrium established between the rate of solids deposition on the membrane surface and the rate of solids removal from the surface. The position of the equilibrium is dependent upon the nature and concentration of dissolved organic substances, which more than likely provide a cohesiveness and adhesiveness to the solids, and the degree of local turbulence at the membrane surface.

For solids-bearing wastewaters, low-pressure (200 psig) reverse osmosis operation was associated with lower product water flux declines than high-pressure (700 psig) operation. This relationship was not observed with carbon-treated secondary sewage where the performance with high- and low-pressure membranes was interchanged. Suspended solids are the only pressure sensitive sewage constituents that could account for this observation. Thus it would appear that high operating pressures increase the density and stability of the flux-reducing, deposited layer on the membrane surface.

Soaking of a severely fouled membrane in an enzyme-active solution was found to be beneficial to the restoration of product water flux, indicating that the enzyme disrupts the adhesion or stability of deposits on the membrane surface.

Differences in reverse osmosis performance between sheet membranes supported in the flat-plate test cells and tubular membranes cast inside fiberglass tubes became manifest only in those instances where alum pretreatment was provided. Calcium sulfate precipitation occurred in the flat-plate test cells due to the existence of substantial areas in the test cell where adequate turbulence was not provided and concentration of the feed water stream to saturation was effected. The product water flux in these situations was diminished by two factors: reduced effective membrane surface area and reduced average effective pressure due to excessive pressure drop through the test apparatus.

In view of the observations made during this program and other information bearing on the matter, it is quite evident that the renovation of even relatively untreated municipal wastewaters by the reverse osmosis process is technically feasible, although the ultimate productivity and economic status of the process have yet to be determined. Further improvements in, and studies with, newly developed and emerging membrane materials will result certainly in improved product water fluxes and even perhaps greater specific pollutant rejections with resulting higher quality product water. Concomitantly, the development of an acceptably performing low-pressure reverse osmosis operation could reduce both capital and operating costs.

The results obtained indicate that further investigation is necessary to realize the goal of practical municipal wastewater renovation by reverse osmosis systems. Laboratory-scale reverse osmosis test apparatus, while serving an extremely important function, has certain limitations that require the conduct of further tests under full-scale conditions. Of most importance is the inability to operate small units at practical product water recovery ratios without either violating minimum wastewater flow conditions or employing wastewater recirculation. Low flows provide insufficient turbulence to control solids deposition and to prevent the creation of excessively high salt concentrations and associated high osmotic pressures adjacent to the membrane surface that reduce drastically the effective pressure and the resulting water flux. Recirculation can cause modified and unrealistic wastewater characteristics that may influence test results in a way not experienced in a full-scale plant where recirculation need not be practiced.

To take full advantage of the technological progress and momentum of the development of the reverse osmosis process related to other applications and to substantiate the laboratory-scale observations made during the program reported herein, the operation of an appropriately sized reverse osmosis pilot plant at a sewage treatment facility is recommended. The pilot plant should be designed specifically to establish the necessary operating conditions and parameters for sustained performance and to provide realistic full-scale cost data on the process. It also is recommended that the field activity be supported with a series of laboratory-scale investigations designed to establish initial operating conditions for the pilot plant, to explore rationally, quickly, and conveniently alternate operating criteria, and to investigate in greater detail the nature of, and means of controlling, the fouling of reverse osmosis membranes by municipal wastewaters.

Section II

INTRODUCTION

Rapidly increasing populations and expanding industrial activities are placing greater and greater demands on fresh water supplies that are relatively static in availability and in some cases even decreasing as the result of pollution. Recognition by the Department of Interior of the need to augment the nation's natural water resources through the desalination of brackish and marine waters has resulted in major advances in the technology and development of suitable processes. It has become apparent however that perhaps a much better source of water for reclamation by these methods is municipal wastewater, since it contains far fewer dissolved minerals and is always available relatively near the intended use.

Several other water resource management objectives also can be achieved concomitantly--more effective wastewater treatment and water pollution control, and a general improvement in the mineral quality of the nation's water supplies. Refractory materials, both mineral and organic, not removed by conventional sewage treatment processes are effectively reduced in concentration by desalination processes. Overdraft of underground reservoirs and the resulting degradation of the groundwater due to irrigation and other natural and artificial recharge practices could not only be checked, but the quality could be enhanced by the planned replenishment of these groundwaters with desalinated and renovated municipal wastewater. Indeed, a net removal of salts and refractory organics from the nation's water resources could be effected and the waters restored to their more natural quality.

Of the many processes capable of demineralizing water, reverse osmosis appears well suited to the renovation of municipal wastewater. Processes requiring a change of phase--distillation and freezing--are better suited for more saline waters since their performance and costs are relatively independent of salt concentration. Of the comparatively low-energy desalination processes, utilizing semipermeable membranes, only the reverse osmosis process possesses the intrinsic advantage that the treatment boundary or interface requires the transport of just purified product water and not the pollutants.

Whereas conventional wastewater treatment processes require a multitude of steps to perform partial and in a few cases very high removals of wastewater constituents, the reverse osmosis process is capable of performing a much superior treatment in fewer operations. Dissolved salts, organic substances, and insoluble suspended matter are all removed in the same procedure.

The potential application of the reverse osmosis process to the treatment of municipal wastewater early in its development was appreciated by the Federal Water Quality Administration. Through the aegis of this and other agencies of the Department of Interior, the reverse osmosis process has been brought in a decade from the state of a laboratory curiosity to the threshold of practical utility.

But where applied like other "tertiary" treatment processes that have demonstrated technical feasibility when preceded by one or a combination of conventional treatment processes, the economic practicability is difficult to establish. Because the reverse osmosis process effects only a separation and concentration and not a conversion of wastewater constituents, it must be accompanied by other processes--processes which treat the resulting concentrated reject stream from the reverse osmosis unit for subsequent disposal and which perhaps prepare the wastewater for the reverse osmosis unit, and processes which are specifically attuned to the attributes and which can take full advantage of the reverse osmosis process. Thus the whole system from the headworks to the outfall must be considered if a rational basis is to be provided upon which to assess the technical and economical utility of an overall wastewater renovation system embodying reverse osmosis.

THE REVERSE OSMOSIS PROCESS

Basic elements of the reverse osmosis process consist of the membrane, a means for providing a high-pressure differential across the membrane, and a support for the membrane against this pressure differential. To meet these requirements various geometries have evolved, including circular flat-plate membrane stacks contained within cylindrical pressure vessels, tubular membranes contained within porous tubes, and flat membrane sheets spirally wound.

A number of different membrane materials possess the favorable osmotic properties of relatively high product water flux and low or no solute transport. Noteworthy among these are of course various forms of cellulose acetate, which to date are the only formulations that have found extensive use in the desalination of nonpotable waters.

Membranes can be prepared to provide a fairly wide range of known salt rejection characteristics. The salt rejection and product water flux capabilities of a reverse osmosis membrane are determined by, in addition to formulation, the membrane annealing temperature and time employed during its manufacture. Since solute rejection increases and product water flux decreases with increasing annealing temperature and time, a high salt rejection is associated generally with a low liquid flux, and vice versa.

The useful life span of a reverse osmosis membrane is that period of time during which the membrane retains an acceptable product water flux. Upon use a membrane exhibits a product water flux decline as a result of two factors--intrinsic membrane compaction or reorientation and materials deposition on the membrane surface. The intrinsic flux decline is a function of membrane formulation, operating pressure, and membrane annealing temperature and is relatively small but significant in extent. The magnitude of the flux decline associated with the deposition of materials from the wastewater varies from insignificant to excessive and is related to the nature and composition of the wastewater, the hydraulic conditions prevailing near the membrane surface, the degree of solute concentration or product water recovery effected by the process, and other operating parameters.

Operating pressure of reverse osmosis units must be sufficiently high to overcome osmotic pressure and to provide a driving force for acceptable water flux. Upper limits on operating pressure are imposed by the economics of producing equipment capable of maintaining the high pressure differentials, and the ability of the membrane to structurally withstand the pressure. Since the magnitude of the osmotic pressure is directly related to the salt concentration, typical operating pressures for desalination of sea water containing approximately 35,000 mg/l of dissolved solids and of brackish water containing about 4,000 mg/l are 1,500 and 750 psig, respectively.

Reverse osmosis equipment used for the renovation of municipal wastewater, which contains from 500 to 1,500 mg/l of total dissolved solids, could be operated at pressures lower than have been used in other applications--pressures perhaps as low as 200 psig.

An important operating variable in reverse osmosis is the product water recovery ratio, or the amount of water produced from the total quantity processed. The highest recovery at which the process can be operated is dependent usually upon the concentration of low-solubility inorganic compounds and organic substances present in the feed water. As the feed water proceeds through the processing equipment, concentration of wastewater constituents occurs due to removal of water through the membrane and substances thus formed can coat the membrane and reduce the water flux. The effective concentration is even greater at the membrane surface than in the bulk liquid due to the buildup of a boundary layer. The magnitude of this concentration polarization is a function of the hydraulic conditions in the wastewater channel; turbulent flow produces a lesser effect than does laminar flow. Also, the product water quality deteriorates quite rapidly as recovery ratios are increased above 90 and approach 100 percent, due to the extremely large salt concentration effected in the wastewater stream.

Whereas a product water recovery ratio near 50 percent is maximum for sea water desalination operations, recovery ratios of 80 or 90 percent and higher appear feasible in the renovation of municipal wastewater with proper preconditioning of the feed water.

THE PROGRAM

In general, this program was directed to the definition of a municipal wastewater renovation system, utilizing the reverse osmosis process and considering associated pretreatment and post-treatment operations, which is optimum in terms of operating characteristics and costs. Specific objectives were to establish the relationships between wastewater feed quality and reverse osmosis performance, to determine the effects of selected feed water additives and conditioning on reverse osmosis performance, to investigate the relative effects of high-pressure and low-pressure operation on reverse osmosis performance, and to develop a computer model of the reverse osmosis process for use in a wastewater treatment simulation program.

The response of the reverse osmosis process to municipal wastewaters of different character was determined by laboratory-scale testing of conventional cellulose acetate membranes with sewages ranging in quality from raw to activated carbon-treated secondary and with digester supernatant. The wastewaters were further modified with selected chemical additives and operations. A limited number of tests were performed with more advanced membranes to establish their performance characteristics.

A computer model of the reverse osmosis process was developed and programmed for use in the Federal Water Quality Administration Executive Digital Computer Program for Preliminary Design of Wastewater Treatment Systems.

Section III

LABORATORY PROCEDURES

Accurate laboratory duplication of full-scale sewage treatment plant facilities and sewages is difficult if not impossible. A good alternative is the use of sample sewages under controlled laboratory conditions, so that test results then may be related to similar operating conditions experienced in real treatment facilities.

SEWAGE FEED WATERS

Daily sewage samples were collected for use in the reverse osmosis test equipment. The samples, representing qualities of effluent ranging from carbon-treated secondary sewage to digester supernatant,were collected at the County Sanitation Districts of Orange County Sewage Treatment Plant No. 1, Fountain Valley, California and the Pomona Water Reclamation Plant, Pomona, California. The Orange County collections were made between 7:00 and 7:30 a. m. on weekdays and 10:30 to 11:30 a. m. Saturdays. Samples from Pomona were obtained at 11:00 a. m. weekdays and 4:00 p. m. Saturday and Sunday.

Table 1 presents average feed water qualities of the various sewages used in this program.

Due to the summer discharges of sugar refinery wastes into the Fountain Valley collection system, all sewages originating from Fountain Valley after 8 April 1969 may have an unusally high organic content, affecting tests between Tests 52 and 96. Also the carbon-treated secondary sewage was of two qualities. In Tests 2 through 8 a relatively high-quality sewage was used from four serial carbon columns wherein the last was just regenerated. All subsequent tests with carbon-treated secondary sewage utilized feed water originating from three serial partially exhausted carbon columns while the fourth was undergoing regeneration of the carbon. This difference did not result in noticeable variations in the monitored feed water quality indicators, but nonetheless, may be a factor influencing the reverse osmosis membrane performance.

Alum-treated, sand-filtered sewage from Fountain Valley was collected from the pilot water reclamation plant operated by the Orange County Water District. All alum-treated sewages from Pomona were processed and filtered in the laboratory.

APPARATUS

Tests were conducted in assemblies representing two different membrane geometries--sheet and tubular. The flat-plate test cells shown in Figures 1 and 2 had been used for many years in conjunction with sea water and brackish water treatment and provided a readily available, proven means of conducting the experimental program. Different types of membranes could be tested easily in these flat-plate cells.

Table 1

AVERAGE FEED WATER QUALITY

(mg/l)

		EC*	Total COD	NH_4-N	Organic N	NO_2-N	NO_3-N	Total PO_4-P	MBAS
Pomona Wastewater									
Carbon-treated Secondary Sewage		1125	15	11.0	1.5	0.074	2.12	10.0	0.13
Secondary Sewage		1340	43	7.6	2.3	0.046	8.45	18.5	1.42
Primary Sewage		1560	236	23.6	8.1	0.236	1.34	18.6	2.41
Fountain Valley Wastewater									
Alum-treated Secondary Sewage	Winter	2161	195	21.6	6.0	0.004	0.48	0.6	1.12
Secondary Sewage	Winter	2240	144	28.2	5.8	0.053	1.87	9.3	1.14
	Summer**	2290	115	26.4	3.9	0.090	0.65	7.6	0.92
Primary Sewage	Winter	2375	-	35.1	8.5	0.042	0.37	7.2	2.10
	Summer**	2673	426	39.0	31.0	0.064	0.54	9.3	-
Raw Sewage	Winter	2833	318	40.4	11.7	0.259	0.87	9.3	2.60
	Summer**	3120	458	34.1	18.7	0.062	1.05	6.0	0.50
Digester Sewage	Winter	13100	3190	413	256	0.028	18.5	2.8	28.3

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*Electrical Conductivity, µmhos/cm at 25°C

**Summer sewage at Fountain Valley contains a waste discharge from a sugar beet refinery.

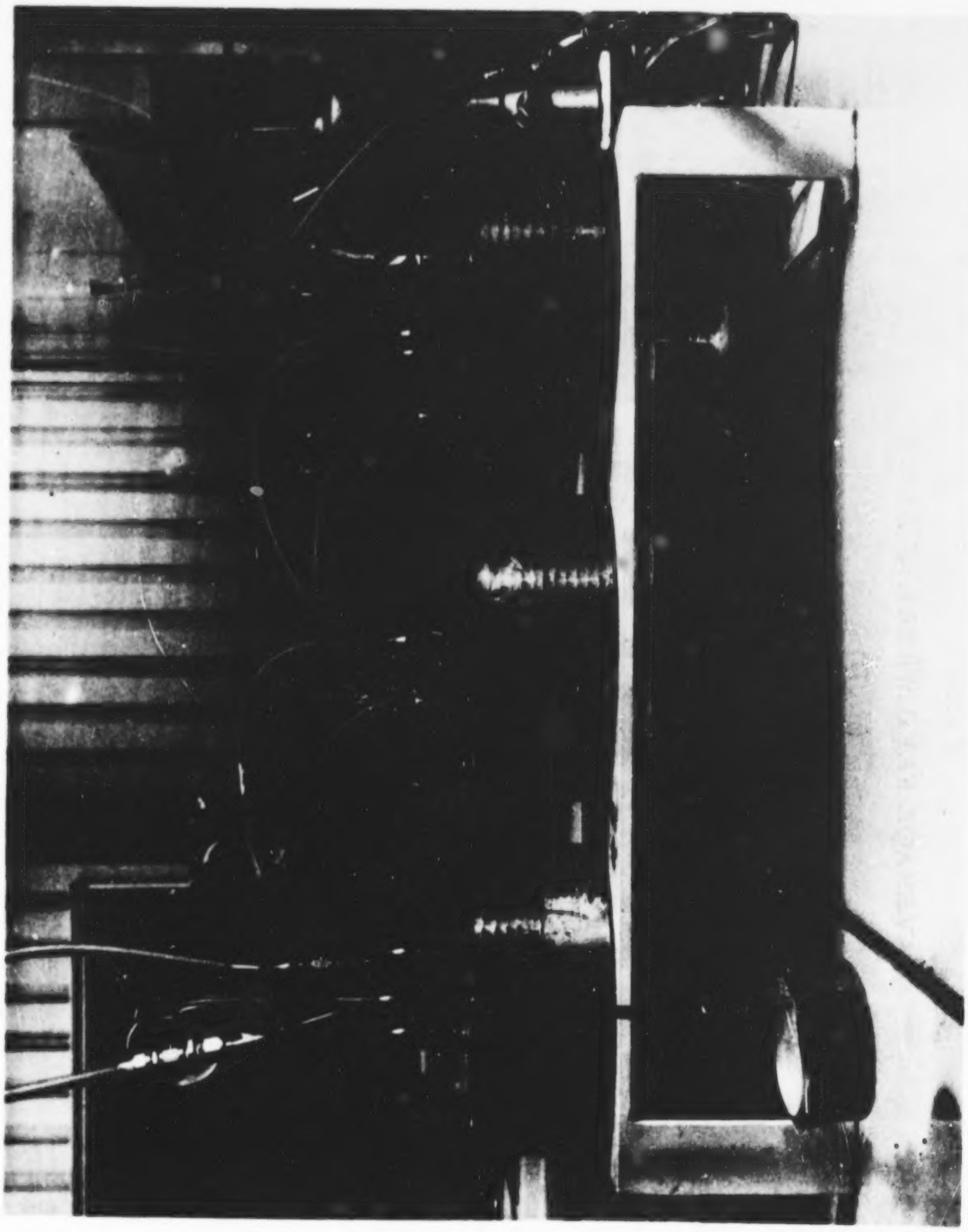
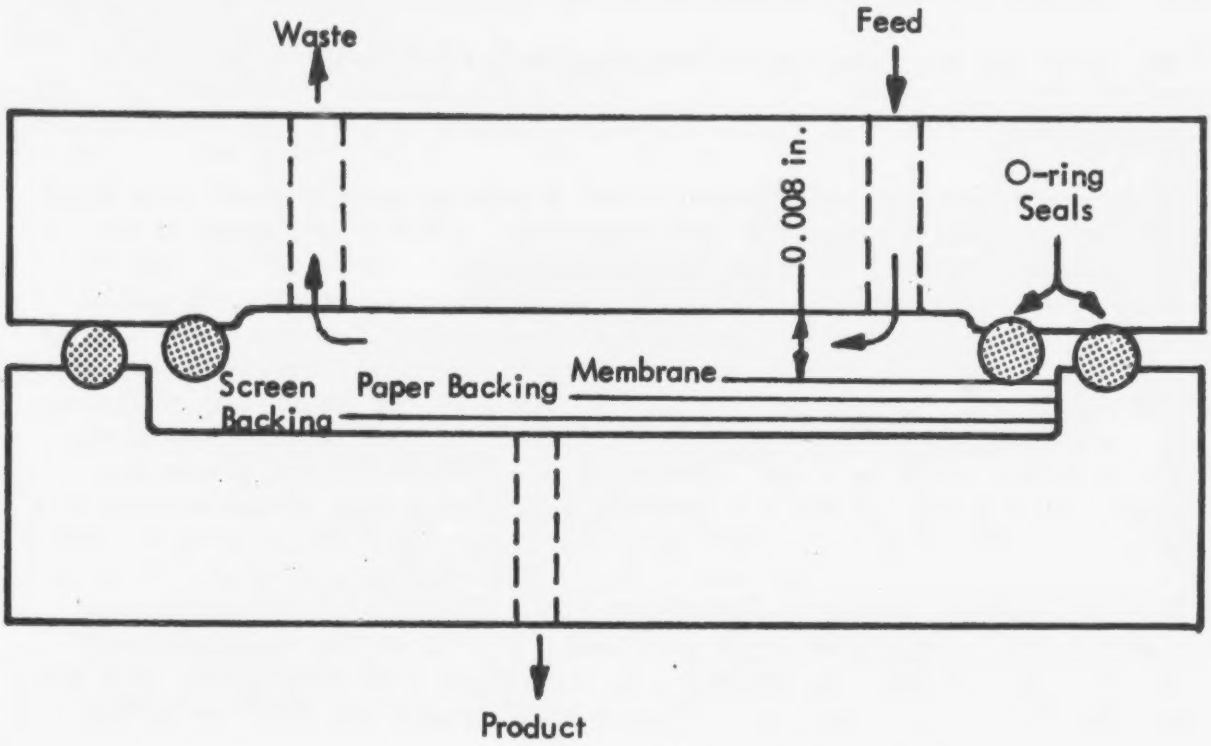
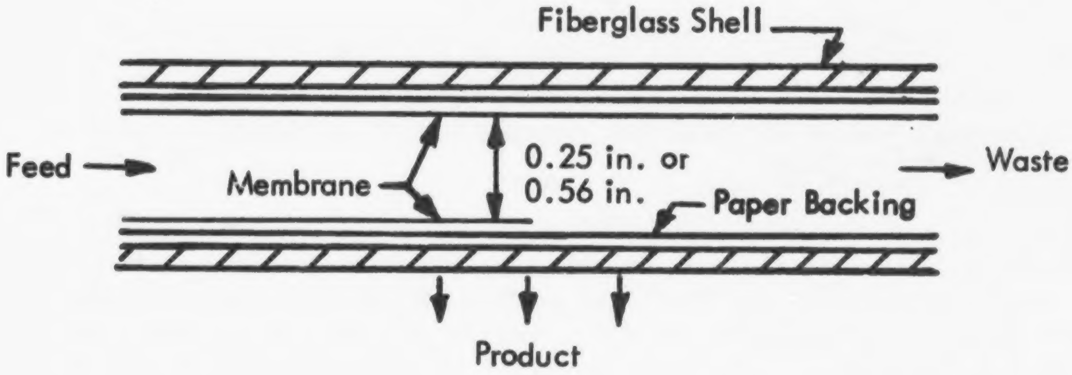


Figure 1. FLAT-PLATE TEST APPARATUS


Waste
Feed
0.008 in.
O-ring Seals
Screen Backing
Paper Backing
Membrane
Product

Flat-Plate Test Cell


Fiberglass Shell
Feed
Membrane
0.25 in. or 0.56 in.
Paper Backing
Waste
Product

Tubular Test Cell

Figure 2. LABORATORY MEMBRANE CONFIGURATIONS

Tubular membrane configurations were tested with the support apparatus pictured in Figures 2 and 3. These stands were used in the evaluation of both the 0.25- and 0.56-in. diameter tubular membranes.

A flow sheet for the laboratory test apparatus is shown in Figure 4.

MEMBRANES

The reverse osmosis membranes used in this program were cast from conventional cellulose acetate formulations. Of the two sheet membranes, differentiated by their annealing temperatures in °C, the 68° membrane produced during the first two hours of operation 30 gal/(sq ft)(day), or 29 μg/(sq cm)(sec)(atm),* of product water from a 0.57-percent NaCl solution at 700 psig with an 87-percent rejection of NaCl. The 44° membrane produced 20 gal/(sq ft)(day), or 68 μg/(sq cm)(sec)(atm), with the same feed water but at 200 psig, and possessed lower salt rejections of 24 percent. Different methods of casting tubular membranes introduced small variations in membrane performance and therefore the two types are considered to have different characteristics. The 0.25-in. tubular membrane delivered 23 gal/(sq ft)(day), or 20 μg/(sq cm)(sec)(atm), with the 1-percent NaCl solution at 800 psig, and provided a NaCl rejection of 85 percent. The 0.56-in. tubular membrane provided 15 gal/(sq ft)(day), or 15 μg/(sq cm)(sec)(atm), and possessed an 81-percent NaCl rejection with a 1-percent NaCl solution.

Three 2.5-in. diameter discs were used in series arrangement in the flat-plate test cells, whereas single 14- and 10-in. lengths of 0.25- and 0.56-in. diameter tubes, respectively, were used in the tubular test assemblies.

Virgin membranes were employed at the beginning of each test run.

OPERATING CONDITIONS

All tests were conducted continuously 24 hours a day, seven days a week throughout their duration. All equipment was shut down routinely every eight hours for several minutes to produce a depressurization and backflow of product water through the membrane to cleanse it and help maintain product water flux.

Two operating pressures were utilized in the laboratory program. The 68° sheet membranes and all the tubular units were operated at 700 psig. Some tests were performed on the 68° membranes at 200 psig. The 44° flat-plate membranes were tested at 200 psig. Most of the tests in this program were conducted at a product water recovery ratio of 80 percent, so that the membranes experienced concentrated feed similar to that found in a full-scale plant after 80 percent of the feed

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*1 μg/(sq cm)(sec)(atm) is equivalent to 1.01 gal/(sq ft)(day) at 700 psig.

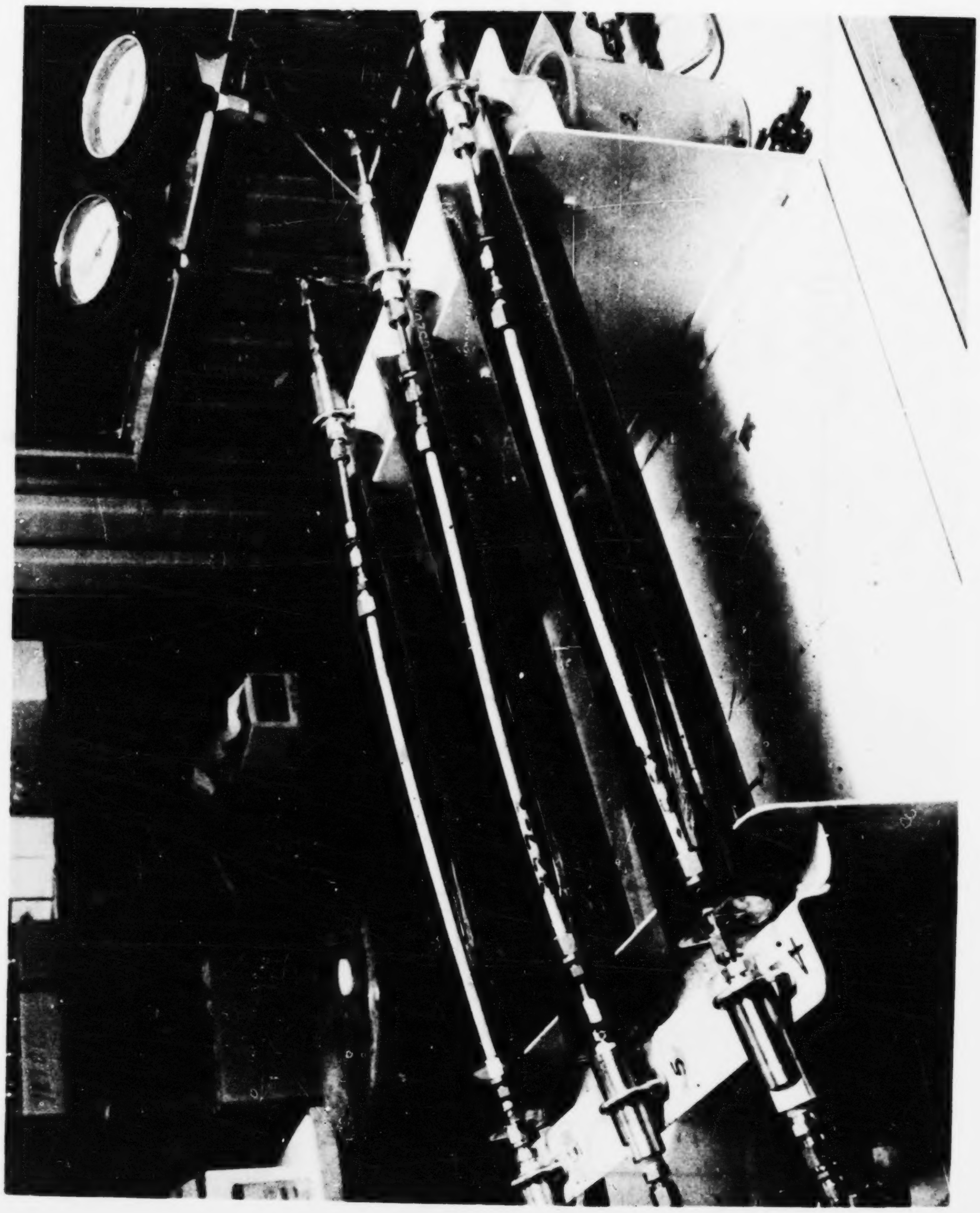

Figure 3. TUBULAR TEST APPARATUS

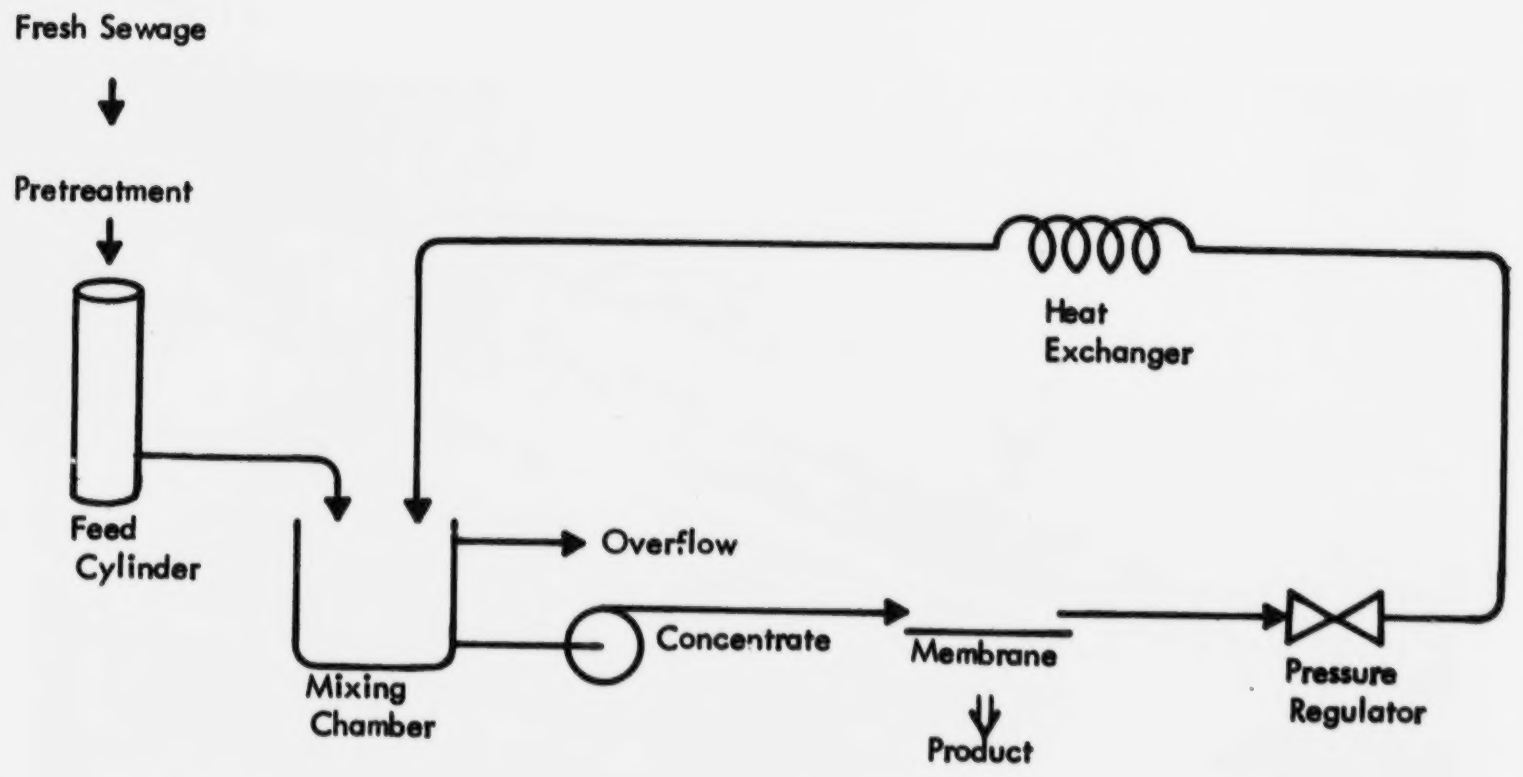
Fresh Sewage
Pretreatment
Feed Cylinder
Mixing Chamber
Overflow
Concentrate
Membrane
Product
Heat Exchanger
Pressure Regulator

Figure 4. LABORATORY TEST APPARATUS FLOW SHEET

water had been removed as product. Excessive salt build-up in the recirculating system was prevented by removal of concentrate from the mixing chamber by means of an overflow tube or blowdown. Initial control of the recovery ratio was done by balancing the product and wasted waters against the feed input. This system was eventually modified in that at the time of concentration of the feed water as determined by mass balance, the electrical conductivity of the concentrate was recorded and thereafter maintained at that level throughout the test. Concentration of all feed waters to the 80-percent recovery condition was effected in the reverse osmosis apparatus with the same membrane utilized for the conduct of the test.

Further modifications of the sewage quality, such as by acid addition, were accomplished in the mixing chamber from which the feed water flowed to the pumps, through the reverse osmosis units, and back again in slightly more concentrated form.

Most tests in this program were conducted at a pH of 5, controlled with sulfuric acid, to assure that no phosphate or carbonate precipitation would occur. However, pH values as high as 8 were employed with one of the more promising additives.

Each unit was operated at a constant throughput that provided calculated nominal Reynolds numbers of about 3,000 for the flat-plate test cells and 5,000 for both tubular cross-sections.

The introduction of additives to the various sewage feeds was intended to prevent product water flux decline caused by the deposition of solids on membrane surfaces. The additives chosen for this study were Zimmite 190 and 120, anionic flocculants; Calgon, a chelating agent; Cyanamer, a dispersant; Biz, an enzyme-active laundry presoaking agent; and alum, a cationic coagulating agent. These additives were maintained at constant dosages throughout most of the test program with the various grades of wastewater, except where noted otherwise. The feed water concentrations of 2.2 mg/l of Zimmite 190 and 100μl/l of Zimmite 120 were selected as the standard dosages based on the manufacturer's recommended range for maintaining clean sewer lines with these products. Calgon and Cyanamer additives were employed at 10 mg/l based on previous successful results on brackish water at this concentration. Biz was used at 20 mg/l on the basis of an arbitrary upper economic level. The optimum dosage of alum was determined daily using jar tests on fresh sewage; typically, these were 125 and 400 mg/l for secondary and primary sewage, respectively.

An inventory of all individual tests performed in this program is presented in Table 2.

The recirculated wastewater quality was initially checked for pH and total dissolved solids by electrical conductivity every hour for 16 hours of the day, but was reduced eventually to bi-hourly sampling for 16 hours. The feed waters were chlorinated and the concentrate was tested twice a day for chlorine residual, which was maintained at less than 5 mg/l.

Table 2

LABORATORY TEST SCHEDULE

Test	Membrane	Feedwater	Pressure (psig)	Additive	References Figure	References Page
2	Sheet	Carbon	700		5	22
3	Sheet	Carbon	700	Alum	7	24
4	Sheet	Carbon	200		14	32
5	Sheet	Carbon	200		15	33
6	Sheet	Carbon	200		13	31
7	Sheet	Carbon	700	ABS	11	28
8	Sheet	Carbon	700	ABS	12	29
9	Sheet	Secondary	700		17	35
10	Sheet	Secondary	200		29	47
11	Sheet	Secondary	200		28	46
12	Sheet	Secondary	700	Calgon	22	40
13	Sheet	Secondary	700	Cyanamer	23	41
15	Sheet	Primary	700	Cyanamer	53	71
16	Sheet	Primary	700		37	55
17	Sheet	Primary	700	Calgon	52	70
18	Sheet	Raw	700		58	77
19	Sheet	Primary	700	Zm 190	41	59
20	Sheet	Raw	700	Zm 190	59	78
21	Sheet	Primary	700		40	58
22	Sheet	Primary	700		39	57
23	Sheet	Digester	700		62	81
24	Sheet	Raw	700	Calgon	60	79
25	Sheet	Raw	700	Cyanamer	61	80
26	Sheet	Secondary	700	Zm 190	20	38
27	Sheet	Digester	700	Calgon	64	83
28	Sheet	Digester	700	Cyanamer	65	84
29	Sheet	Digester	700	Zm 190	63	82
30	Sheet	Secondary	700	Alum	18	36
31	Sheet	Secondary	200	Alum	31	49
32	Sheet	Secondary	200	Alum	32	50
33	Sheet	Secondary	700	Alum-Cy	27	45
34	Sheet	Secondary	700	Alum-Zm	25	43
35	Tube	Secondary	700	Alum-Zm	76	96
36	Tube	Secondary	700	Alum-Zm	77	97
37	Tube	Secondary	700	Alum	70	89
38	Sheet	Secondary	700	Alum-Cal	26	44
39	Sheet	Carbon	700	Calgon	9	26
40	Sheet	Carbon	700	Zm 190	8	25
41	Sheet	Secondary	700	Biz	24	42
44	Tube	Secondary	700		68	87
45	Tube	Secondary	700	Zm 190	73	93
46	Sheet	Carbon	700	Cyanamer	10	27
47	Tube	Primary	700	Zm 190	84	104
48	Sheet	Secondary	700		16	34

Table 2 (continued)

LABORATORY TEST SCHEDULE

Test	Membrane	Feedwater	Pressure (psig)	Additive	References	
					Figure	Page
49	Sheet	Primary	700	Biz	54	72
51	Tube	Carbon	700		66	85
52	Sheet	Primary	700	Zm 190	49	67
53	Sheet	Primary	700	Zm 190	43	61
54	Sheet	Primary	700	Zm 190	47	65
55	Tube	Primary	700	Zm 190	82	102
56	Tube	Carbon	700		67	86
57	Tube	Secondary	700		69	88
58	Tube	Secondary	700	Zm 190	74	94
59	Sheet	Primary	700	Zm 190	42	60
60	Sheet	Primary	700	Zm 190	50	68
61	Tube	Secondary	700	Calgon	75	95
62	Sheet	Primary	700	Zm 190	46	64
63	Tube	Raw	700		92	112
64	Tube	Raw	700	Zm 190	93	113
65	Sheet	Primary	200	Zm 190	55	74
66	Sheet	Primary	700		38	56
68	Sheet	Primary	200	Zm 190	57	76
69	Tube	Primary	700		78	98
70	Tube	Secondary	700	Alum	72	91
71	Tube	Primary	700	Zm 190	81	101
72	Sheet	Primary	700	Zm 120	51	69
74	Sheet	Primary	700	Zm 190	44	62
75	Tube	Secondary	700	Alum	71	90
76	Tube	Primary	700	Alum	79	99
77	Sheet	Carbon	700		6	23
78	Sheet	Primary	700	Zm 190	45	63
79	Tube	Primary	700	Calgon	89	109
80	Sheet	Primary	200	Zm 190	56	75
81	Tube	Primary	700	Zm 190	86	106
82	Tube	Primary	700	Zm 190	83	103
83	Sheet	Primary	700	Zm 190	48	66
84	Sheet	Secondary	700	Zm 190	21	39
85	Tube	Primary	700	Cyanamer	90	110
86	Tube	Primary	700	Zm 190	87	107
87	Sheet	Secondary	200	Zm 190	36	54
88	Sheet	Secondary	200	Zm 190	35	53
89	Tube	Primary	700	Biz	91	111
90	Sheet	Secondary	200		30	48
91	Tube	Primary	700	Zm 190	88	108
92	Tube	Primary	700	Zm 190	85	105
93	Sheet	Secondary	200	Zm 190	34	52
94	Sheet	Secondary	200	Zm 190	33	51
95	Sheet	Secondary	700	Zm 190	19	37
96	Tube	Primary	700	C-31	80	100

MEASUREMENTS

At the beginning of the program, samples taken for chemical analysis were 24-hr composites of the feed, waste, and product waters collected every two days. Once membrane performance with regard to waste constituent rejection had been established, chemical analyses were performed as a check on gross membrane deterioration and concentrate quality and were conducted on 24-hr composite samples every week. The following constituents were monitored and analyzed in accordance with procedures outlined in the Twelfth Edition of *Standard Methods for the Examination of Water and Wastewaters*, *American Public Health Association, Inc.*, or *FWQA approved alternate* methods: pH, electrical conductivity, total dissolved solids, chemical oxygen demand, biochemical oxygen demand, organic nitrogen, ammonium, nitrite, nitrate, total phosphate, and methylene blue active substances.

Electrical conductivity was determined by using a conductivity bridge with a 4.5-ml capacity cell.

Total dissolved solids were measured by weighing the residue from a filtered (0.45μ) and evaporated sample.

Total chemical oxygen demand was determined by potassium dichromate-sulfuric acid digestion for two hours and ferrous ammonium sulfate titration to the ferroin indicator endpoint; any chloride present in the sample was complexed with mercuric sulfate.

Ammonium contained in samples was distilled from Kjeldahl flasks and collected in boric acid solution. The amount of ammonia in the distillate was determined either colorimetrically at 467-mμ wavelength in a spectrophotometer following Nesslerization (less than 5 mg/l ammonia) or volumetrically by titration with sulfuric acid using methyl red-alphazurine mixed indicator (greater than 5 mg/l ammonia).

Organic nitrogen content of samples was ascertained by difference between the results of total unoxidized nitrogen and ammonia nitrogen analyses. Total unoxidized nitrogen concentration was determined by conversion to ammonia through sulfuric acid digestion (in the presence of potassium sulfate and copper sulfate), collection in boric acid solution by alkaline distillation, and detection either by Nesslerization or acid titration.

Analyses for nitrite content were performed on samples by reacting with sulfanilic acid, developing color with N-(1-naphthyl)-ethylenediamine dihydrochloride, and determining optical density at a wavelength of 550 mμ in a spectrophotometer.

Nitrate analyses were performed spectrophotometrically using a brucine-sulfanilic acid and sodium chloride color development procedure by the method of Kahn and Brezenski from "Determination of Nitrate in Estaurine Waters," *Environmental Science and Technology*, 1, 488-49(1967).

Total phosphate analyses were performed on samples by digestion with concentrated nitric acid and strong sulfuric acid, color development of the orthophosphate with ammonium molybdate, sulfuric acid, ascorbic acid, and potassium antimonyl-tartrate mixture, and measurement of absorbance at a wavelength of 885 mμ in a spectrophotometer.

Methylene blue active substance was determined by extraction of the methylene blue complex with chloroform and measurement of light absorbance at 650-mμ wavelength in a spectrophotometer.

Hydrogen ion concentration of samples was measured with a pH meter using a glass electrode and calomel reference cell.

Residual chlorine concentrations were determined utilizing the thiosulfate-iodide titration method.

The standard 5-day, 20°C dilution bottle method was used for biochemical oxygen demand determinations; dissolved oxygen analyses were made using the Winkler, azide modification, method.

Collected samples were refrigerated at 0°C prior to analysis to reduce deterioration of various sewage constituents.

Based on ten samplings for each feed water, a ratio between total dissolved solids and electrical conductivity was determined. A value of 0.6 may be considered representative of the TDS:EC ratios. In the case where slightly ionized macromolecules, such as duodecal benzyl sulfonic acid, were added to relatively high-quality feed water, the ratio increased to as high as 0.9 in the feed and recycle waters while remaining near 0.6 in the product stream.

A number of biological oxygen demand analyses were performed to determine the relationship between the BOD and COD values. The raw sewage feed water and wastewater streams had a COD:BOD ratio of approximately 2. The digester, primary, and secondary sewage feed and waste streams had ratios ranging from 3 to 7, with an average of 4, while carbon-treated and alum-treated, sand-filtered sewages provided ratios ranging from 6 to 14, with an average of 6 for the feed waters and 13 for the waste streams. The ratios for the respective product water streams were double the values obtained for the wastewater streams. The increasing difference between COD and BOD with progressing sewage treatment is expected, as the biologically oxidizable materials are gradually removed while the relatively nonbiodegradable constituents remain and increase in relative proportion.

DATA REDUCTION

Membrane performance was measured at the 80-percent or higher recovery levels maintained during each test run. Data acquired during the concentration of the feed to the test level were not included because, at conditions other than fully concentrated feed, membrane behavior is nonrepresentative and data become more ambiguous with the addition of a variable recovery ratio. Initial concentration time varied with product water flux but usually ranged from eight hours to two days.

It was originally believed that a 2-week test period would be adequate to establish long-term membrane performance. Also tests which resulted in a greater than 50-percent flux loss were not considered worthy of further study and were discontinued. Laboratory experience gradually demonstrated that with a testing period of three weeks, ultimate long-term flux could be established with reasonable certainty. Moreover it was established that initial flux declines were not necessarily indicative of future trends. For these reasons, test durations are not the same throughout the period of study.

Initial examination of the data on product water fluxes indicated that most test results may be presented as exponential functions of time. Certain results however do not fit this description, but on closer examination may be seen as approaching a steady-state condition of zero flux decline. In such cases initial decline data are still felt to be best represented in exponential form with the steady-state condition of no decline needing no mathematical representation. Due to the short duration of many of the test runs it would be difficult to ascertain when the mathematical function is no longer consistent with the data. Therefore flux decline data have been calculated using all of the data points presented and are given in the form of the coefficients J_o, k, and a to fit the general equation

$$J = J_o e^{kt \pm a}$$

where J is product water flux in gal/(sq ft)(day), J_o is initial flux, in gal/(sq ft)(day), upon attainment of specified concentration, k is the flux decline coefficient in day^{-1}, t is expressed in days of operation at desired wastewater concentration condition, and a is the standard deviation of the flux decline exponent.

Inasmuch as the ultimate aim of this program was to establish the best process for wastewater treatment by reverse osmosis, the only truly acceptable result, which has been achieved in several instances, is a flux decline of zero or nearly zero. With such results available, the direct comparison of flux declines markedly different from zero becomes a somewhat academic matter. However, the rate of flux decline for a given set of conditions does indicate how rapidly the steady-state flux will be reached and does provide for a standard of comparison when the final flux is not determined in a test.

The flux decline expressions were calculated from 8-hr composited volumes of product, with three data bits per day. The fluxes were converted to their logarithms and with their respective time periods were used to find the best fit of the data by least-squares regression. Membrane performance with respect to constituent rejection was calculated on the basis of what actually contacts the membrane surface at the particular recovery ratio.

Section IV

LABORATORY RESULTS

The test results obtained in this program represent a large number and diversity of factors that influence the performance of the reverse osmosis process. Performance is measured by two characteristics--product water flux and wastewater constituent rejection. The magnitude and temporal variation in product water flux are dependent upon the type or character of feed water, test-cell geometry, membrane type or permeability, operating pressure, product water recovery ratio, and type and dosage of additives. On the other hand solute or pollutant rejection for this application and under the test conditions studied appears to be relatively independent of all the aforementioned factors with the exception of feed water type and membrane permeability.

Product water flux results are presented in the form of figures which also indicate values for all variable test parameters and calculated coefficients for the product water flux decline. All feed waters, except carbon-treated secondary sewage, originating at the Pomona Plant are so designated while feed water supplies from Fountain Valley carry no special designation. Carbon-treated sewage was available only at Pomona.

PRODUCT WATER FLUX

Flat-plate Test Cells

The product water fluxes obtained with the flat-plate test assemblies under a variety of operational conditions are presented according to the type or quality of municipal wastewater.

Carbon-treated Secondary Sewage

Carbon-treated secondary sewage was the highest quality effluent obtainable for this program. This sewage established the best performance in this program for the reverse osmosis process with municipal wastewaters. Figures 5 and 6 represent control tests on carbon-treated secondary sewage with the 68° membrane. The aluminum content of 4 mg/l expressed as alum in the feed water of Test 2 was naturally present. Subsequent tests were not analyzed for their aluminum content. Test 77 was a retrial of Test 2 after several months of operation. The lower product water flux in Test 77 may be attributed to both a practical inability to fully clean the test equipment of the deposits from other sewages and the previously mentioned feed water quality differences between the two sampling dates.

Figures 7, 8, 9, and 10 present values obtained with alum, Zimmite 190, Calgon, and Cyanamer. Again it should be mentioned that Tests 39, 40, and 46 were conducted on equipment that had been used to process wastewaters of much lesser quality. Figures 11 and 12 demonstrated attempts to find the effects of methylene blue active substances on product water flux.

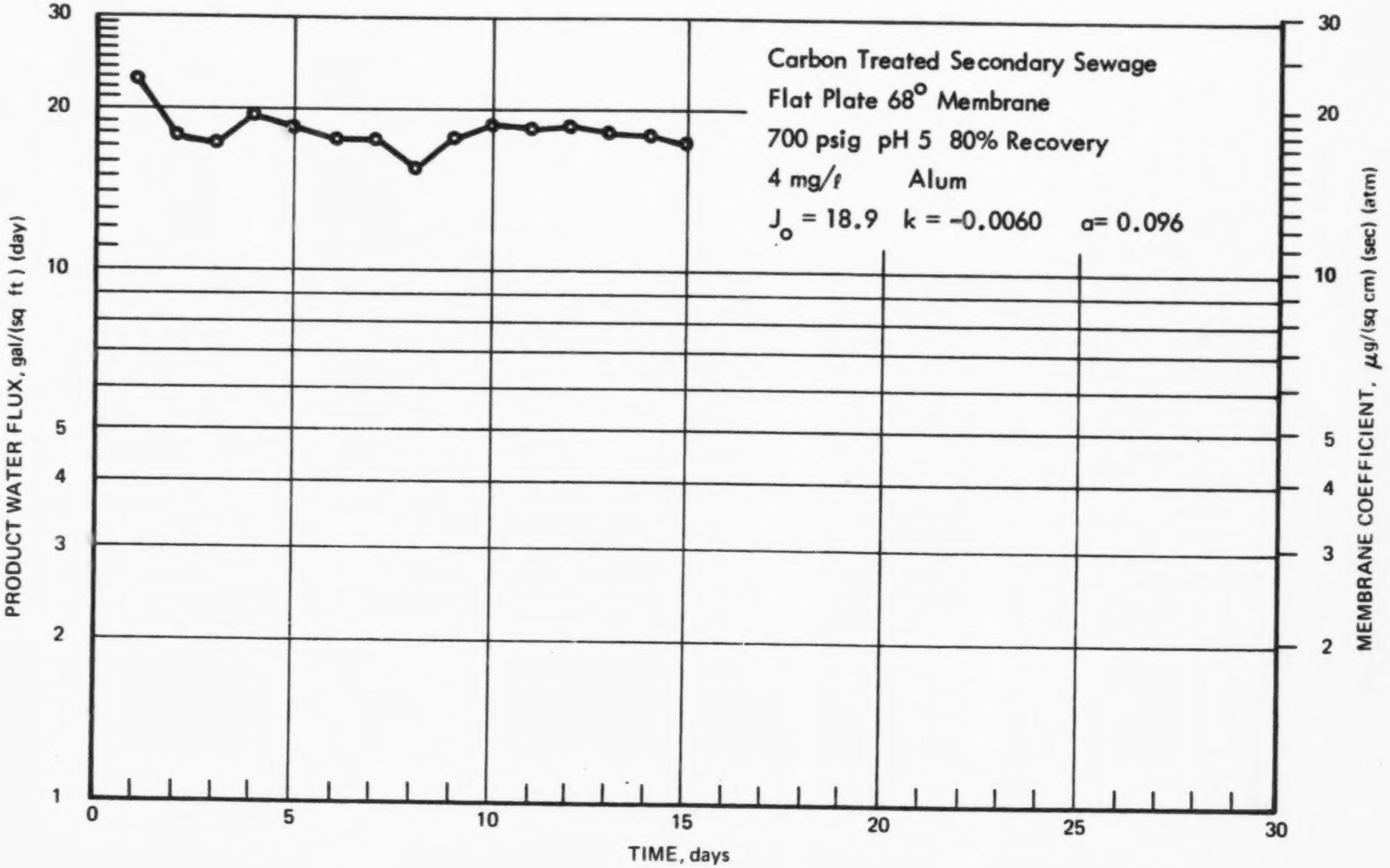

Figure 5. PRODUCT WATER FLUX, TEST 2

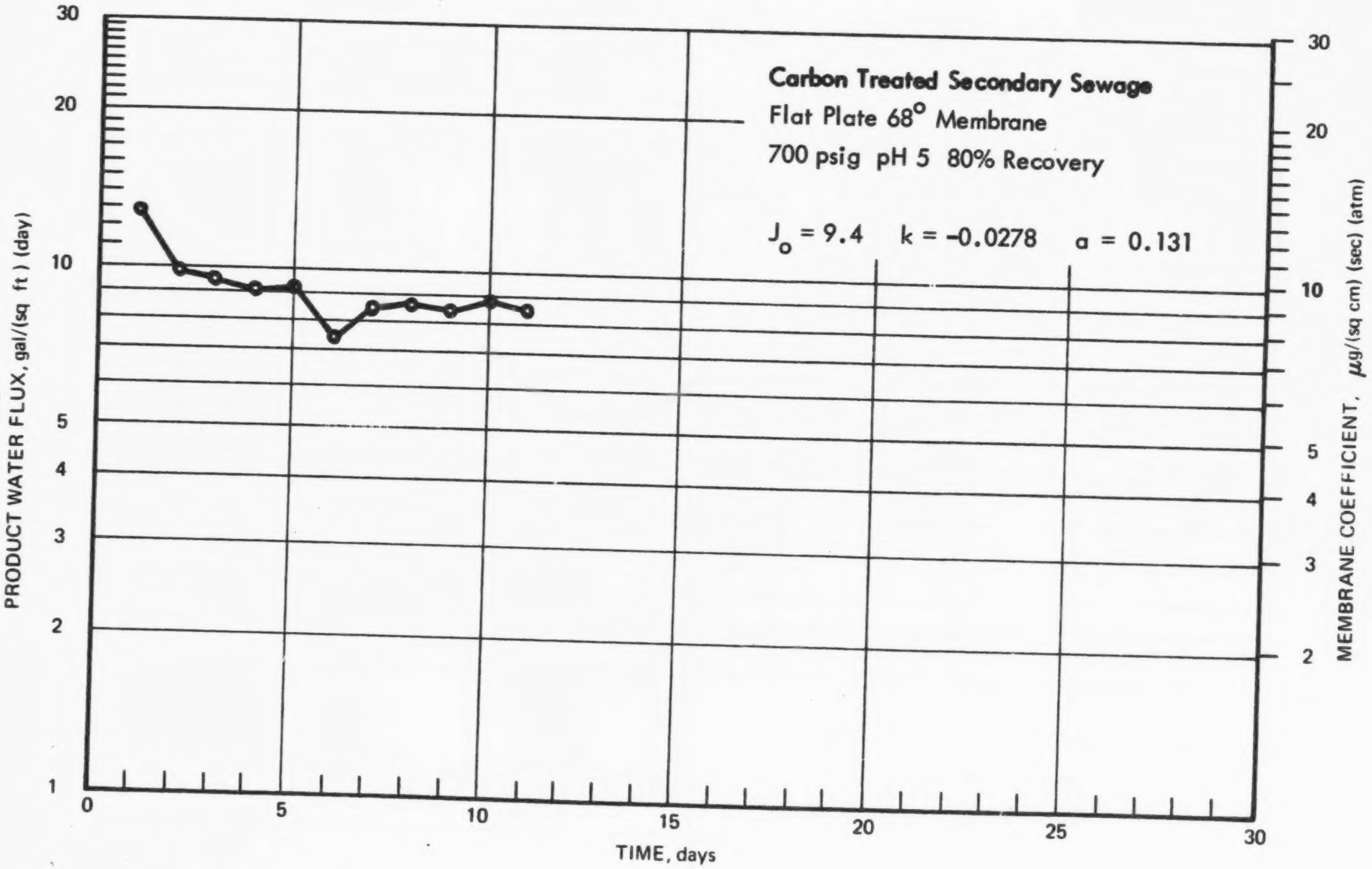

Figure 6. PRODUCT WATER FLUX, TEST 77

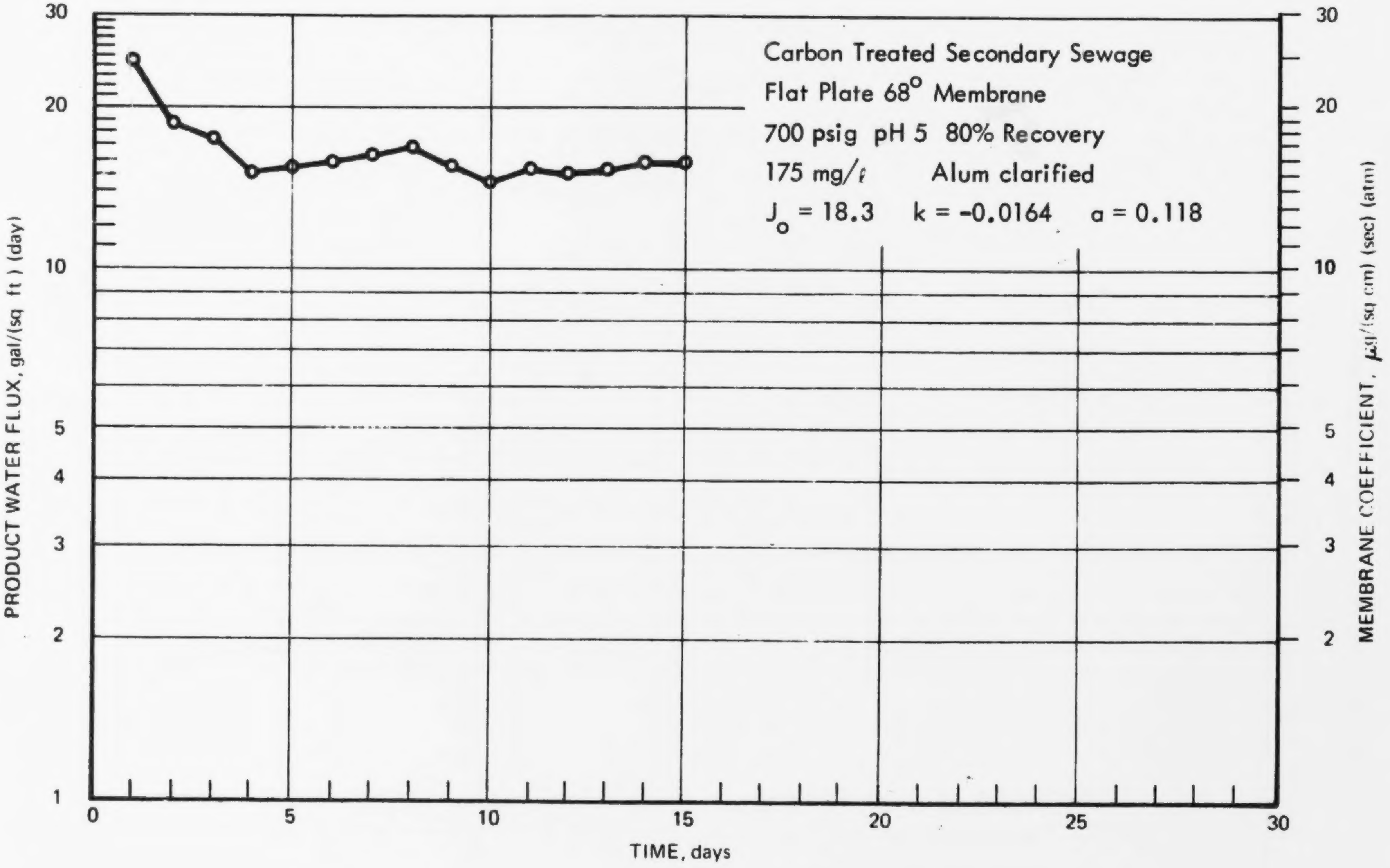

Figure 7. PRODUCT WATER FLUX, TEST 3

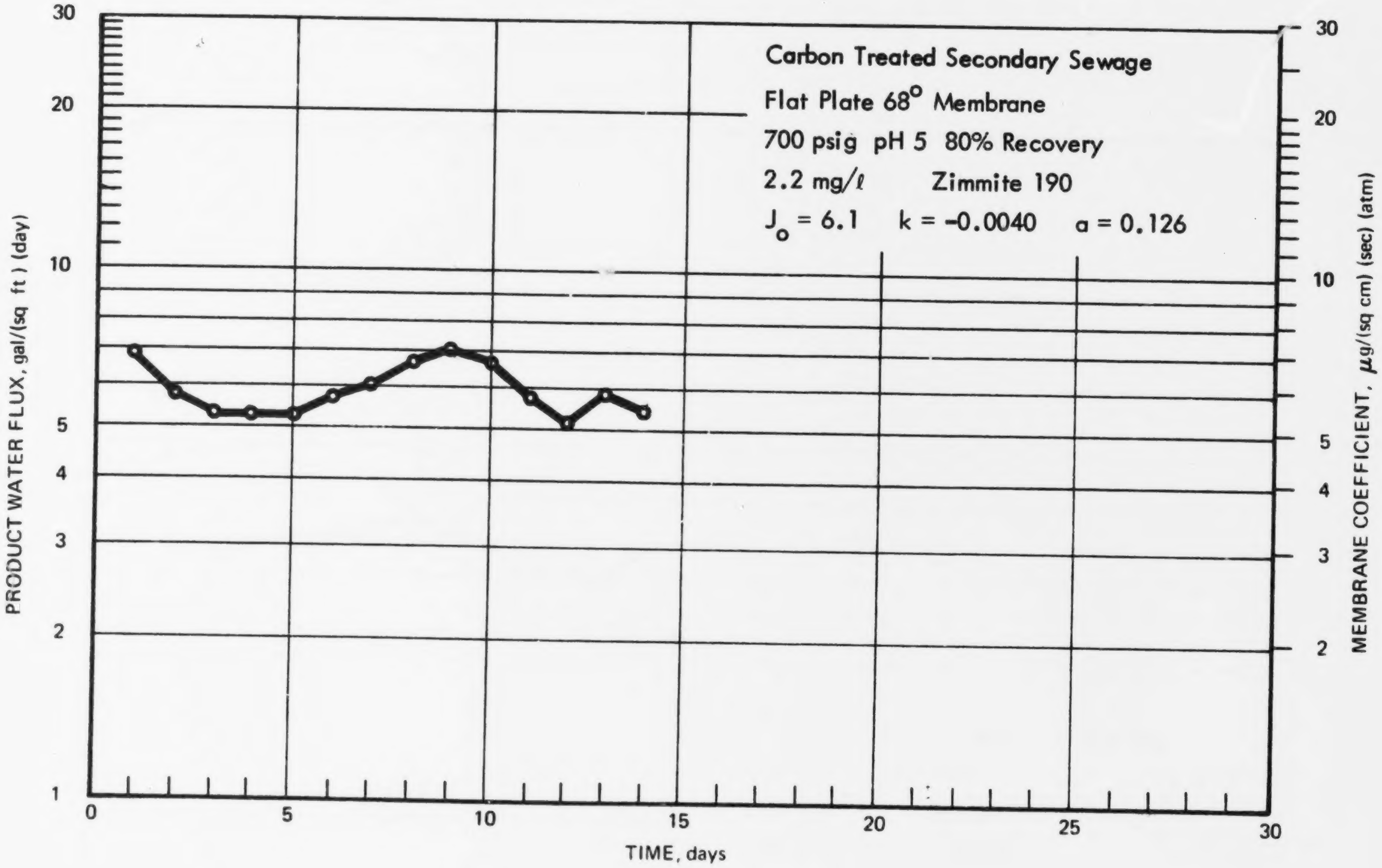

Figure 8. PRODUCT WATER FLUX, TEST 40

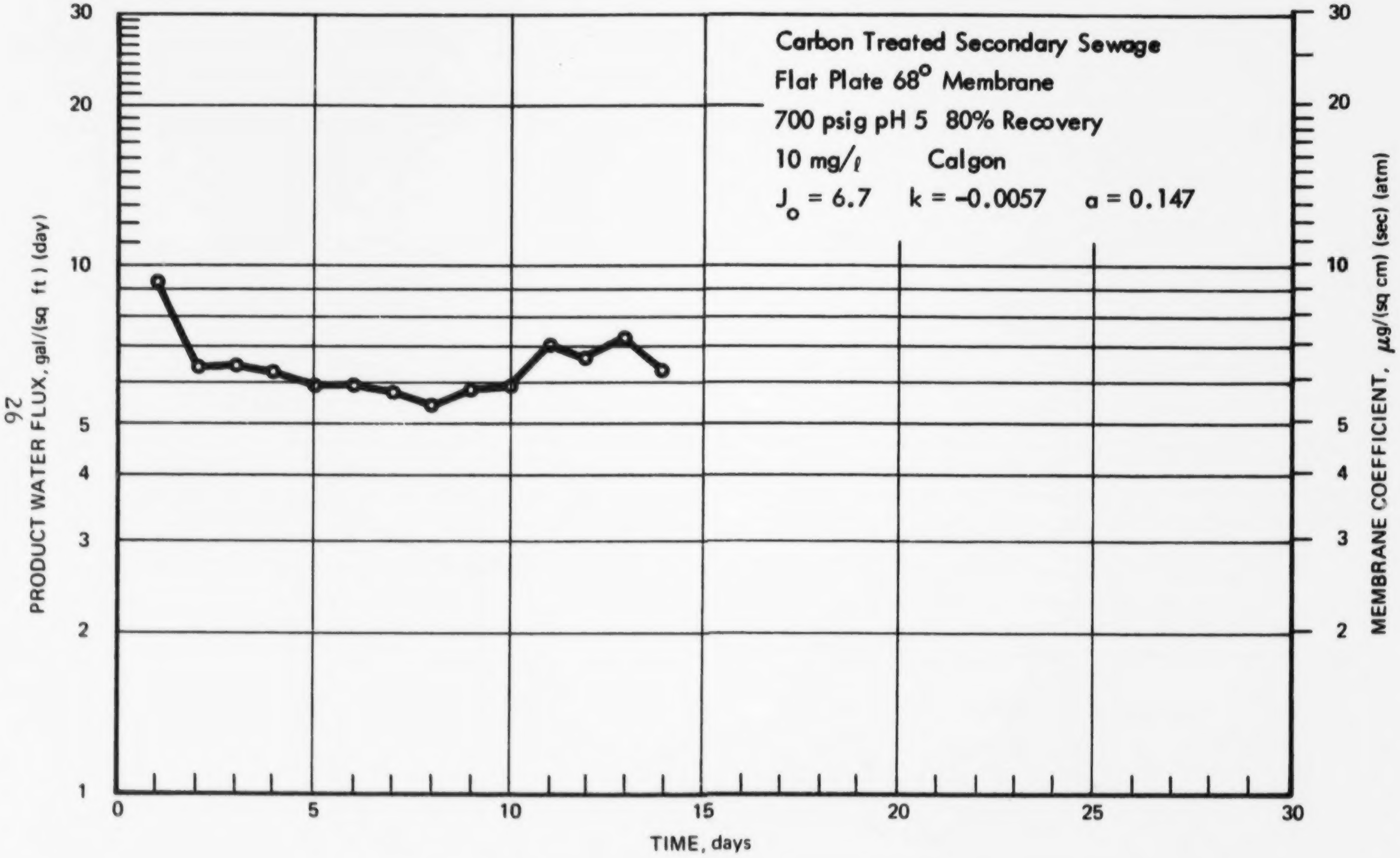

Figure 9. PRODUCT WATER FLUX, TEST 39

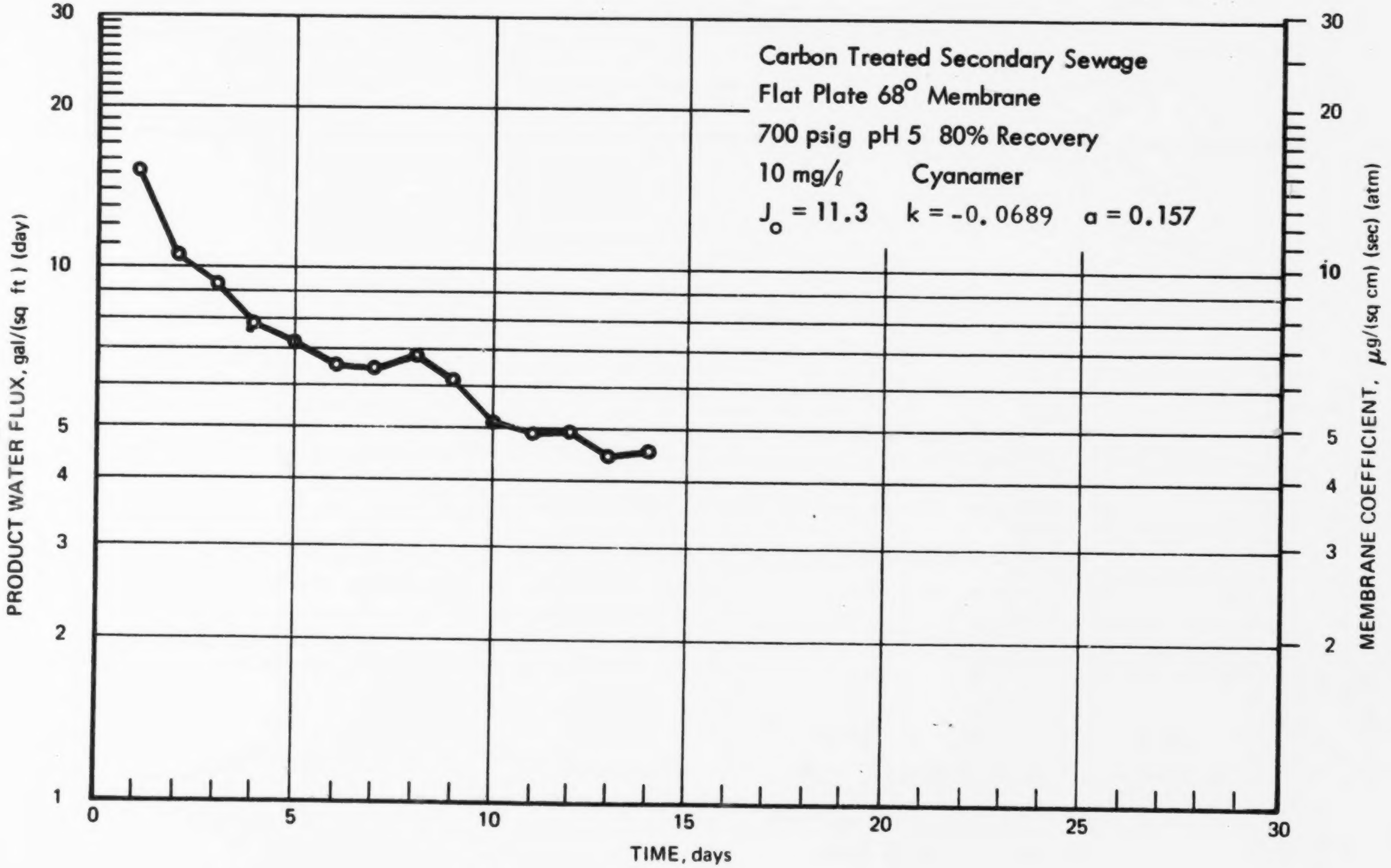

Figure 10. PRODUCT WATER FLUX, TEST 46

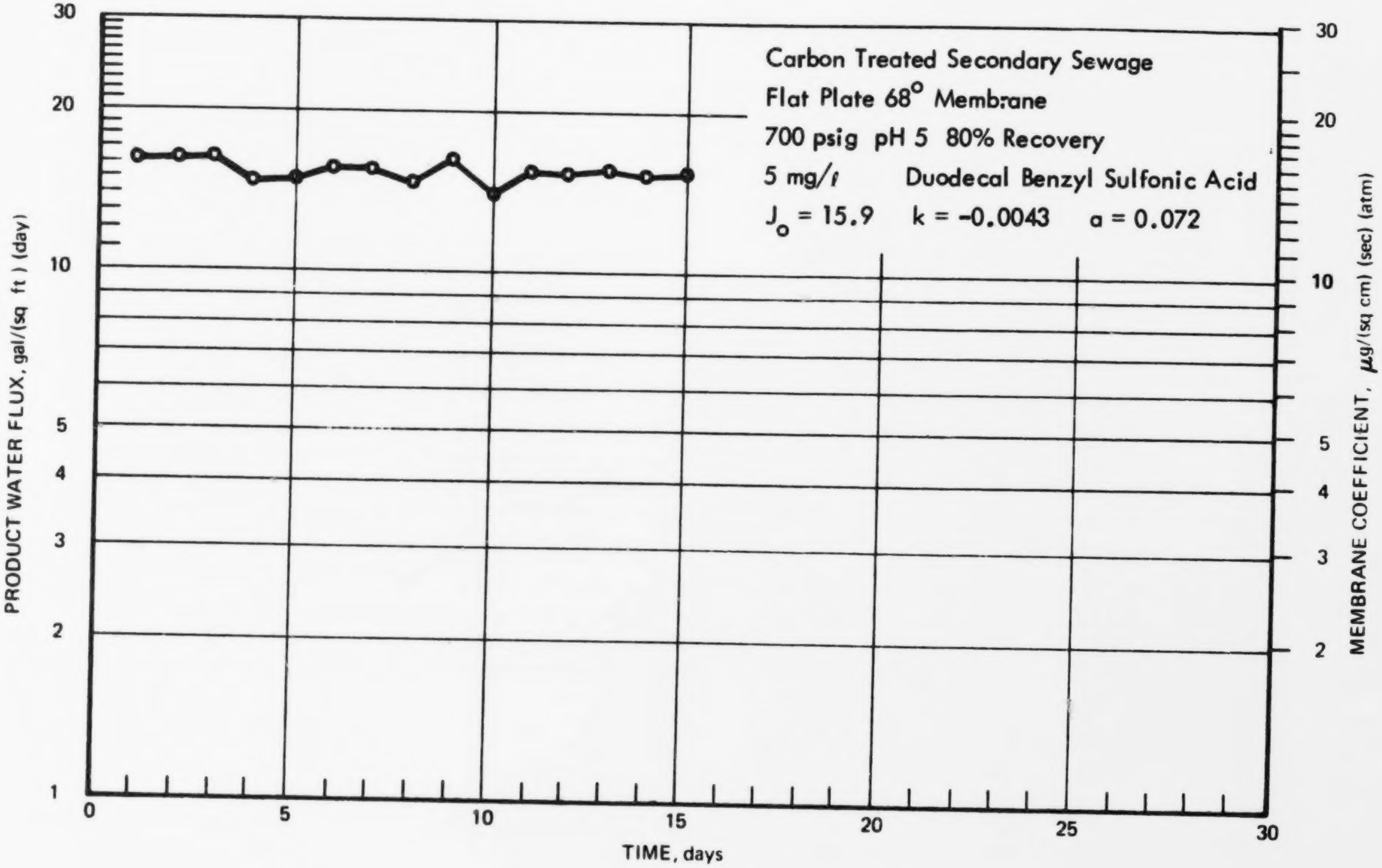

Figure 11. PRODUCT WATER FLUX, TEST 7

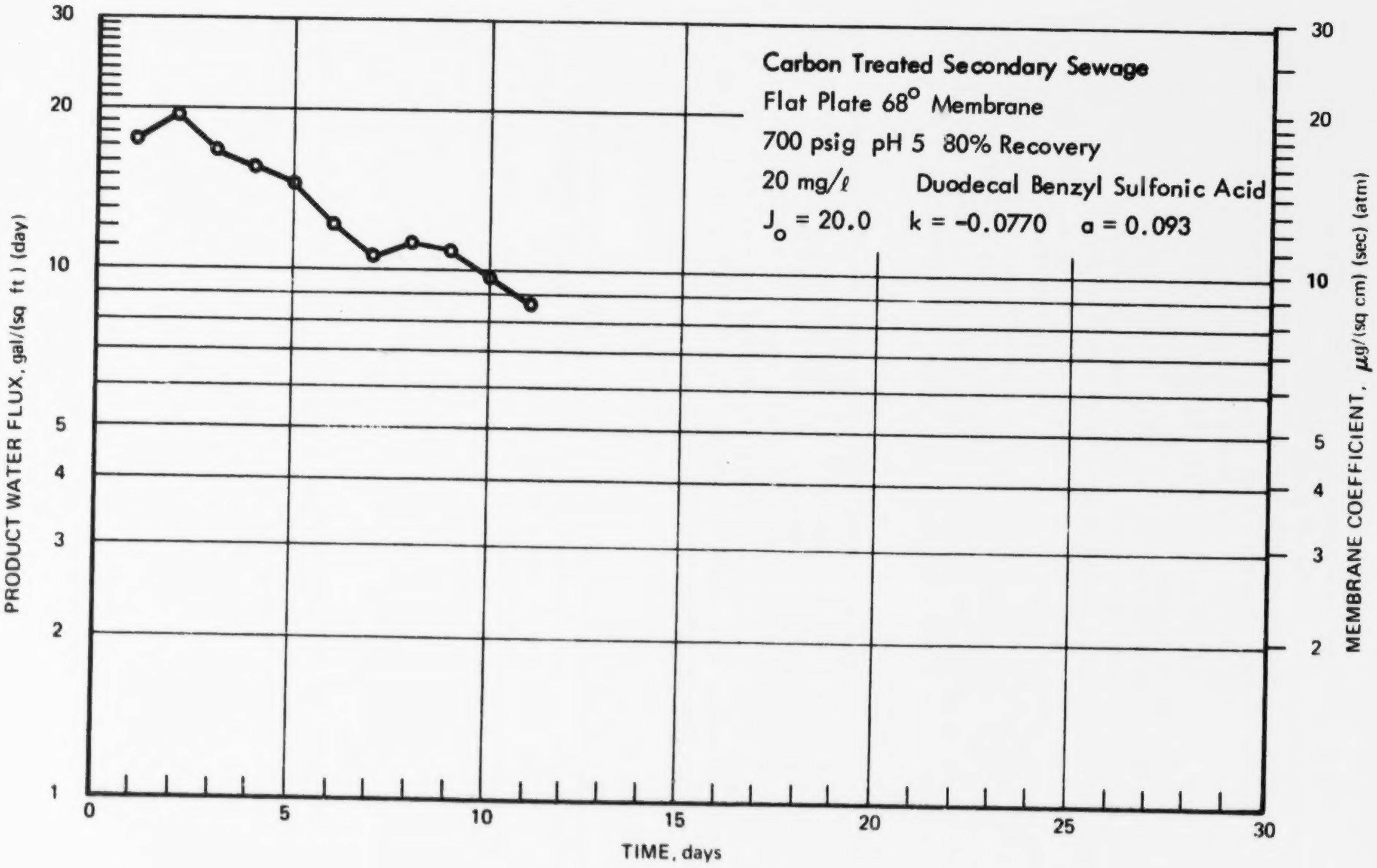

Figure 12. PRODUCT WATER FLUX, TEST 8

The results of low pressure operation at 200 psig on 68°, 55°, and 44° membranes are depicted in Figures 13, 14, and 15.

Secondary Sewage

Secondary sewage with its comparatively low total solids content is of great interest in the processing of municipal wastewater by the reverse osmosis process. The results of high pressure operation are first presented in Figures 16 and 17 which are control tests for the Fountain Valley and Pomona feed waters. Figures 18, 19, 20, 21, 22, 23, and 24 present test results with continuous addition of alum, 1.1 and 2.2 mg/l of Zimmite 190, Calgon, Cyanamer, and Biz. Typical membrane deposits were noted in Test 26 (Figure 20), where the product water flux experienced a steady increase with no apparent cause for the increase in flux. Operating results with dual pretreatment of the feed water by alum and then addition of Zimmite 190, Calgon, and Cyanamer are presented in Figures 25, 26, and 27. In all the tests on secondary sewage with alum pretreatment, the sheet membranes became thickly deposited with calcium sulfate. This did not occur with carbon-treated secondary sewage in Test 3 (Figure 7). An analysis of deposits on the membrane from Test 9 with secondary sewage revealed 98-percent volatile material.

The control tests for low pressure operation with the 68° and 44° membranes were conducted at pH values of 5 and 6 as shown in Figures 28, 29, and 30. Low pressure testing with alum-treated or Zimmite 190-enhanced feed waters is depicted in Figures 31, 32, 33, 34, 35, and 36. The testing with Zimmite 190 was conducted at a pH of 6, based on other test results, and explored various concentrations of the additive to establish the optimum dosage.

Primary Sewage

The successful treatment of primary sewage by reverse osmosis could substantially change the current methods of wastewater treatment by replacing conventional secondary treatment processes. The following tests were conducted with primary sewage at 700 psig. Figures 37, 38, 39, and 40 present the results of the control tests on primary sewage, including experiments to determine the impact of minor variations in operating procedure. Tests 16, 21, and 22 (Figures 37, 40, and 39, respectively) were relatively short-term due to the approach of holidays.

Most of the testing of additives in this program was conducted at fixed dosages and a pH of 5. The possibility that Zimmite 190 might be more effective at a different dosage or a higher pH value led to the series of tests investigating variations in these two parameters. The data from these tests are shown in Figures 41, 42, 43, 44, 45, 46, 47, 48, 49, and 50. The comparative performances of the other additives, including Zimmite 120, an anionic polyelectrolyte, are presented in Figures 51, 52, 53, and 54.

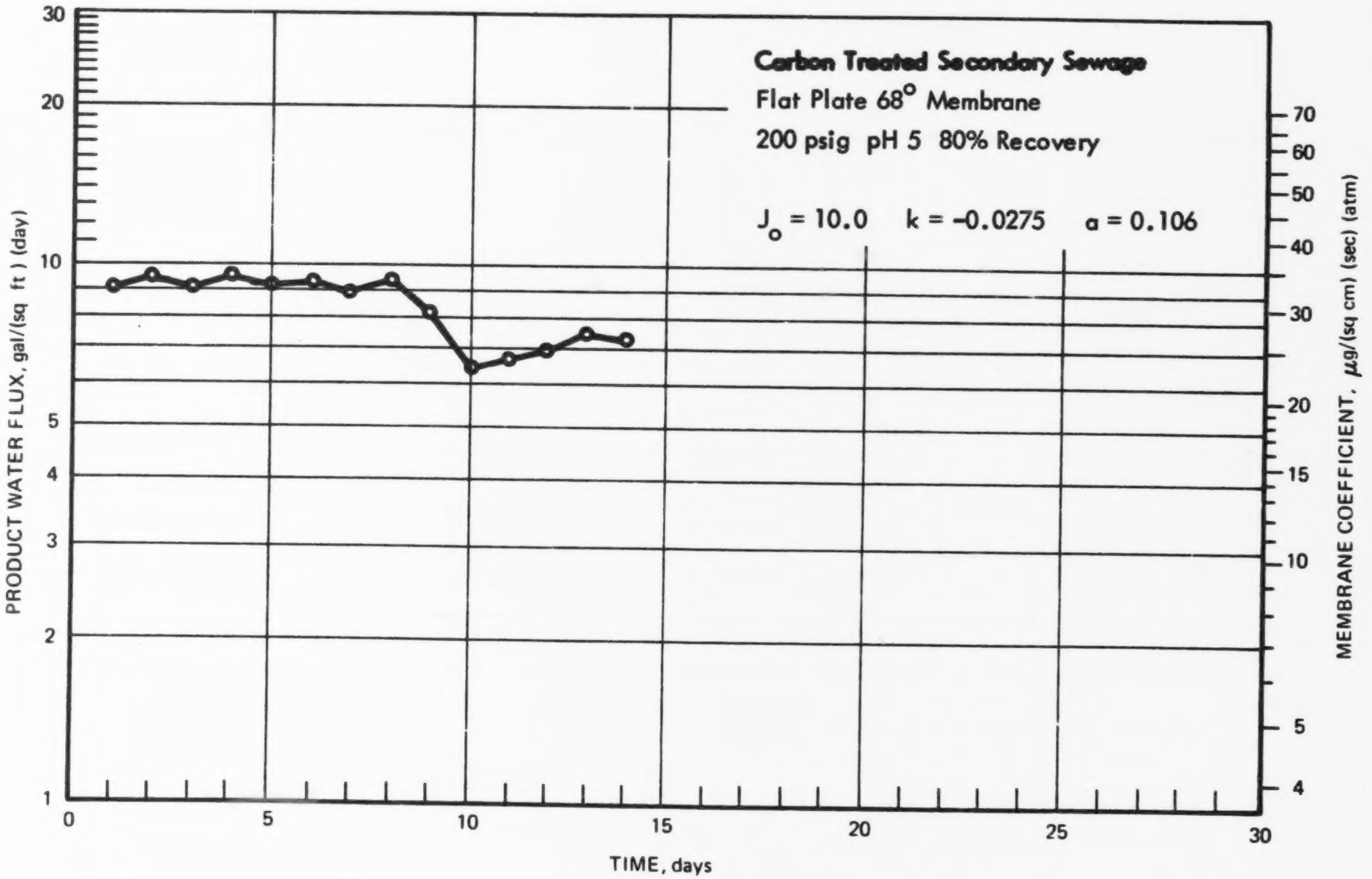

Figure 13. PRODUCT WATER FLUX, TEST 6

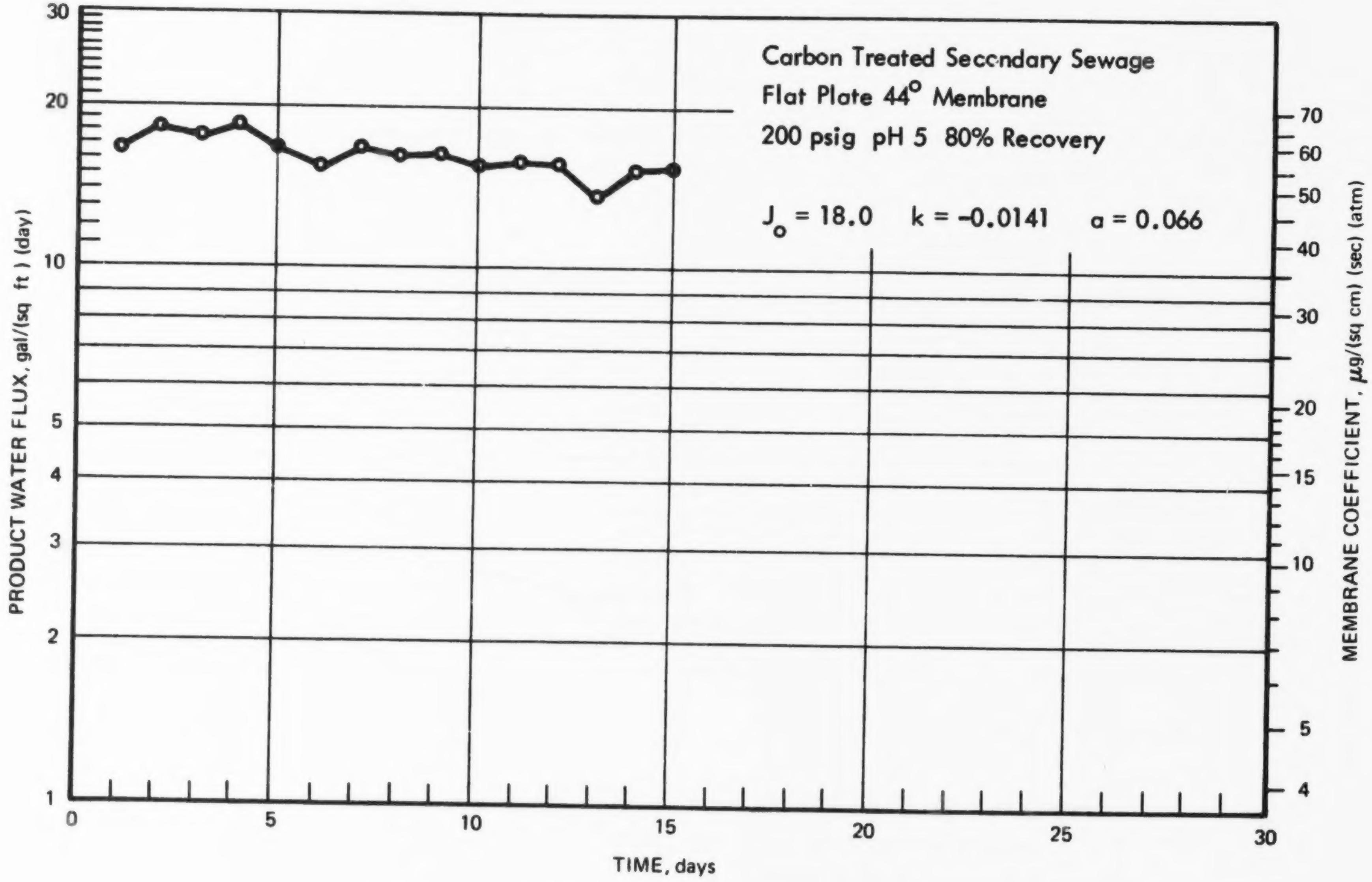

Figure 14. PRODUCT WATER FLUX, TEST 4

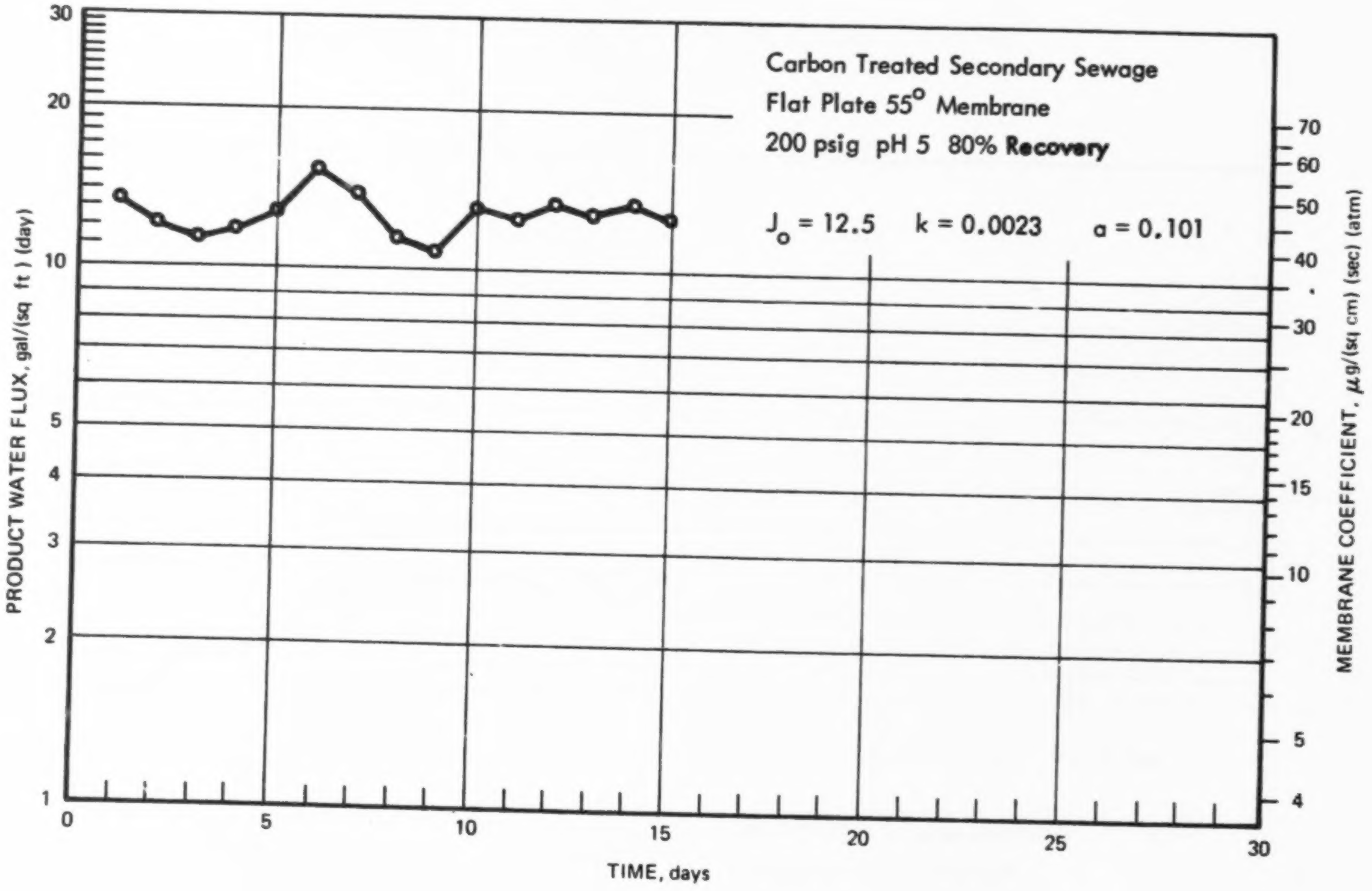

Figure 15. PRODUCT WATER FLUX, TEST 5

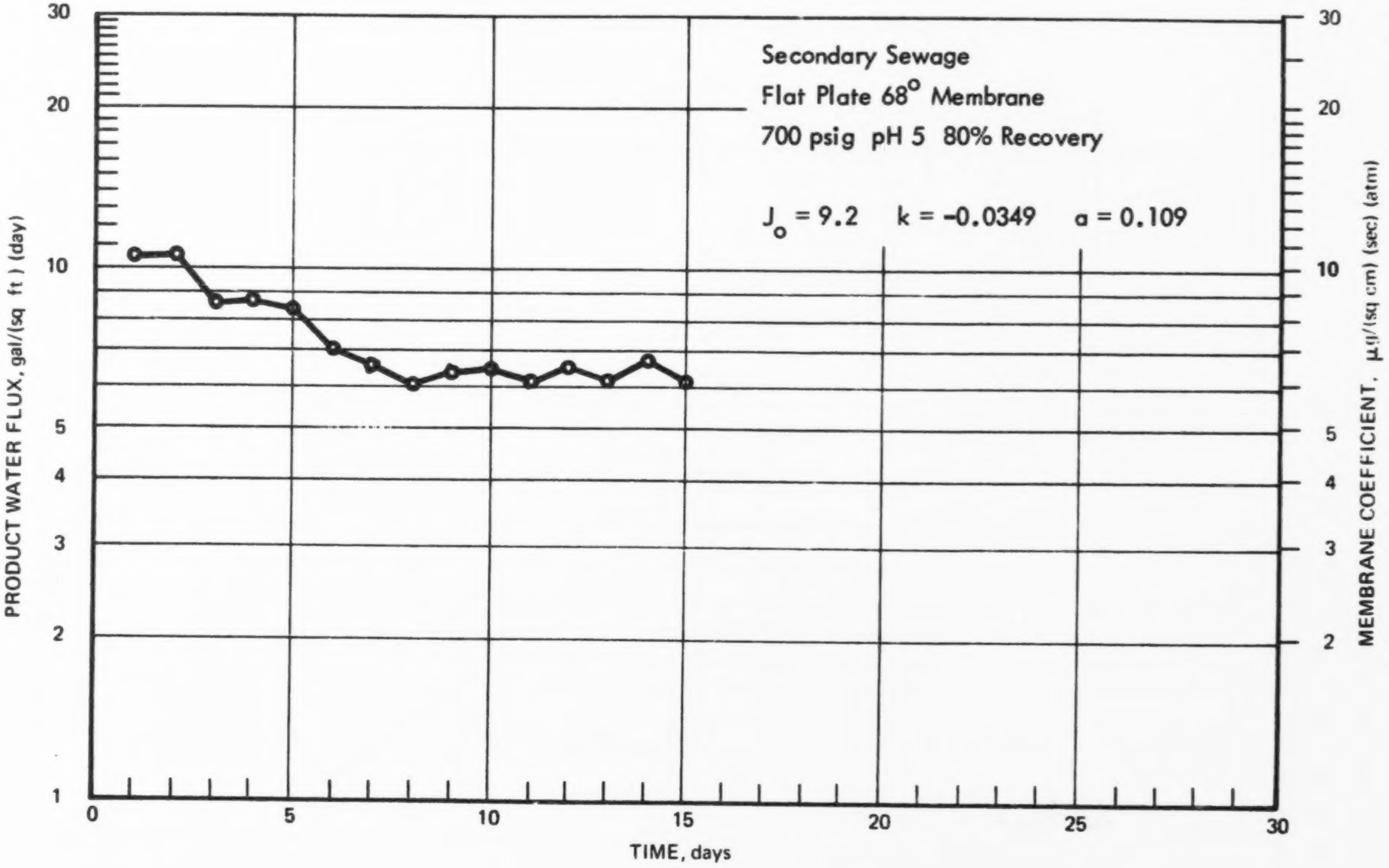

Figure 16. PRODUCT WATER FLUX, TEST 48

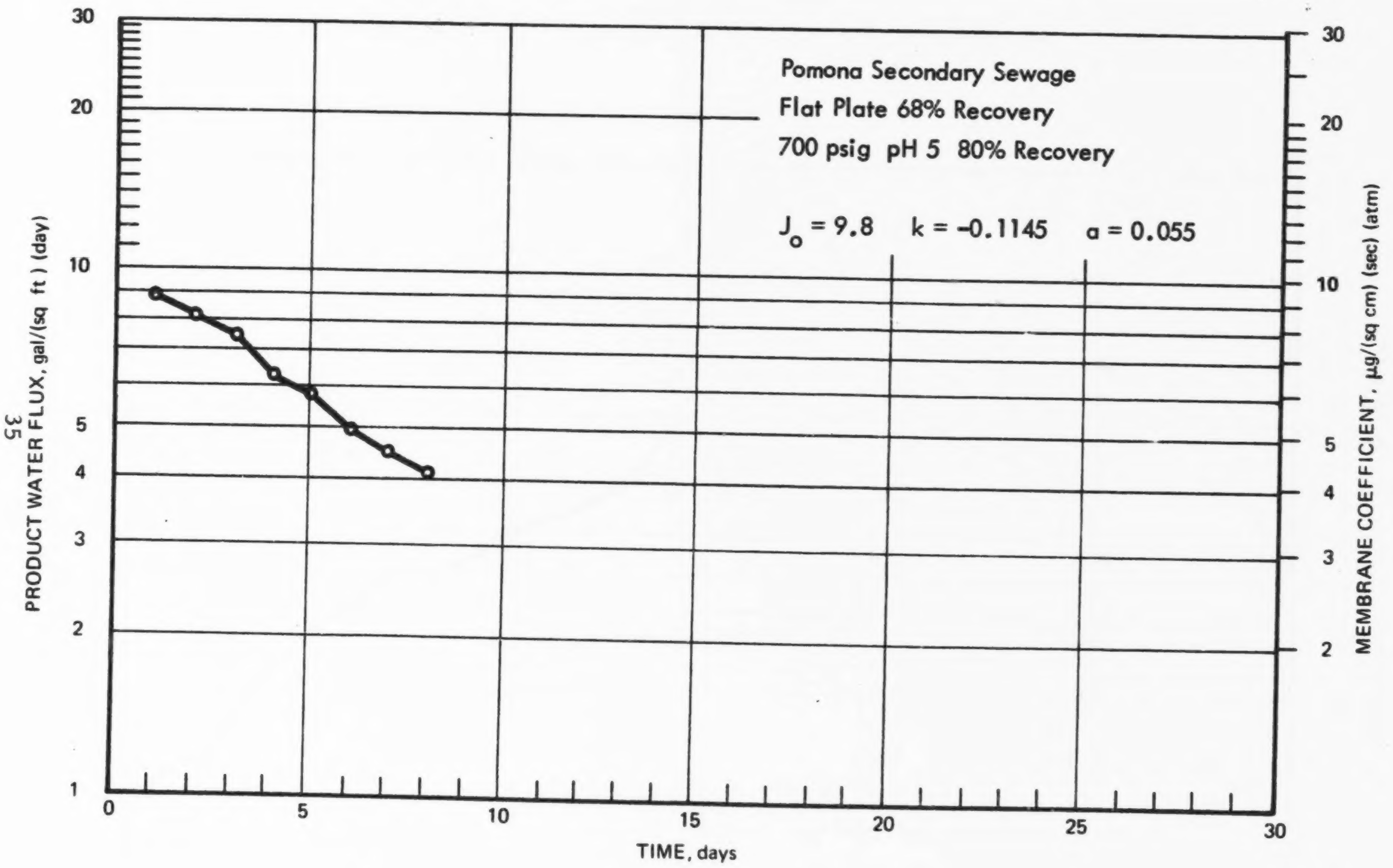

Figure 17. PRODUCT WATER FLUX, TEST 9

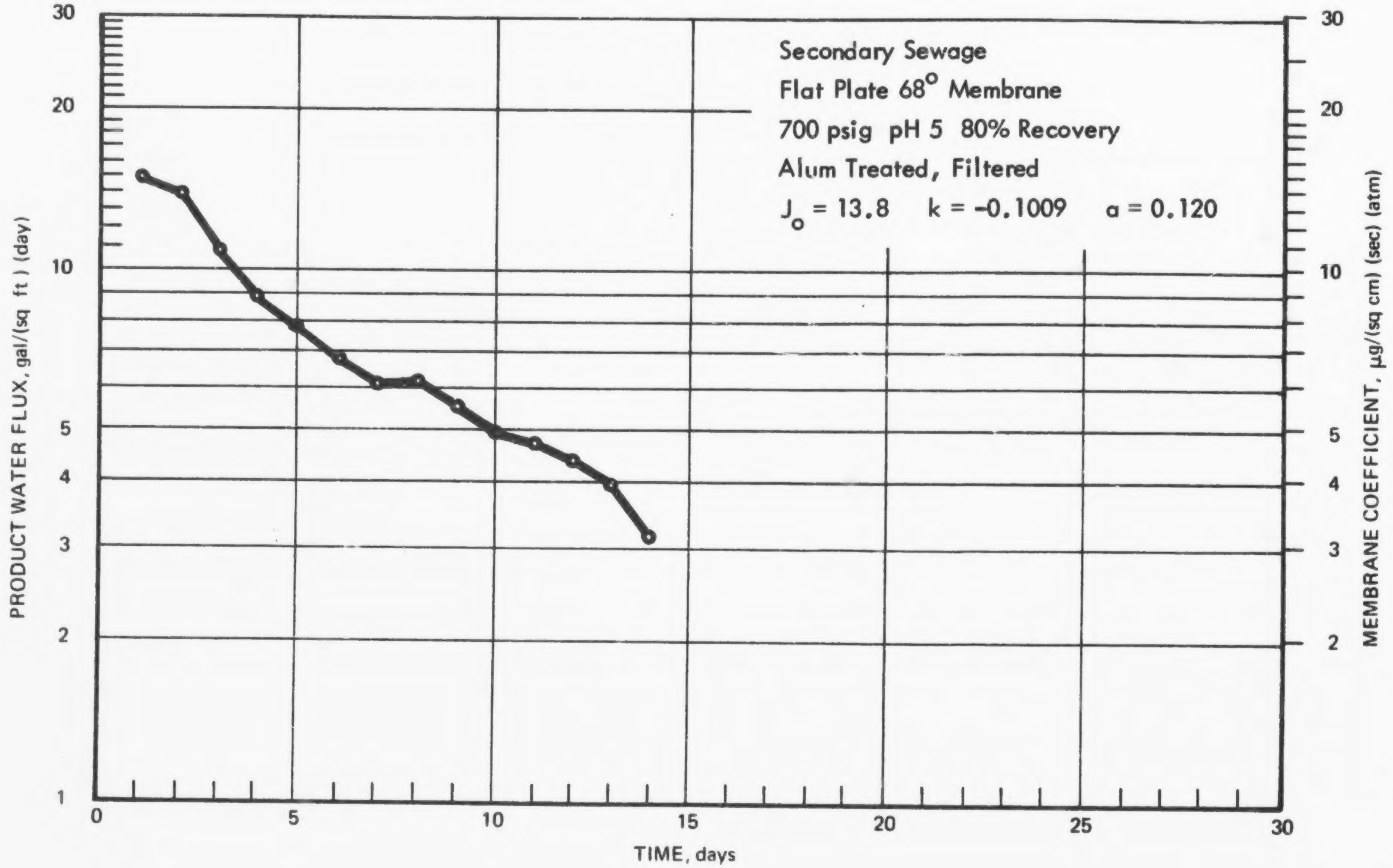

Figure 18. PRODUCT WATER FLUX, TEST 30

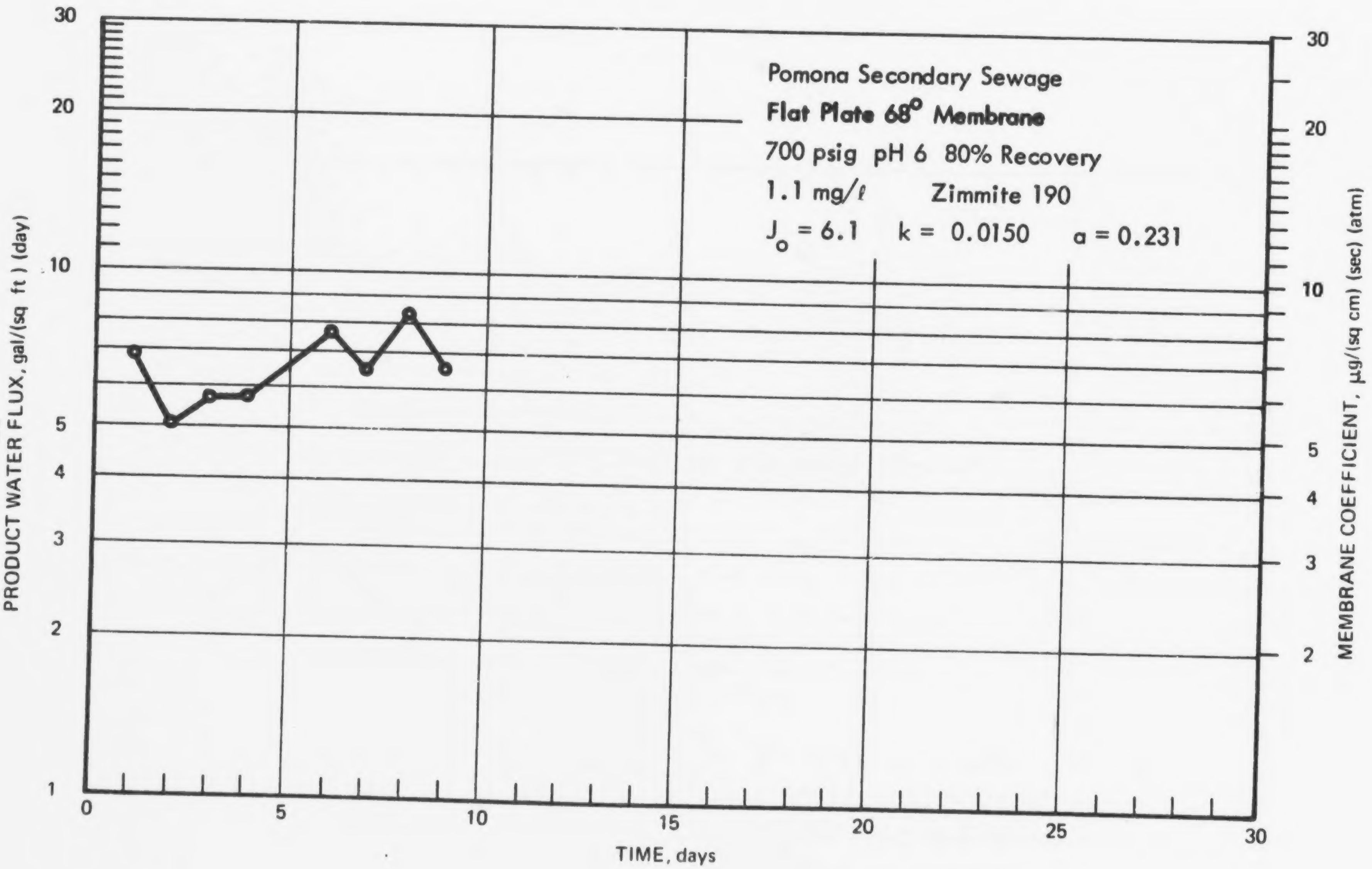

Figure 19. PRODUCT WATER FLUX, TEST 95

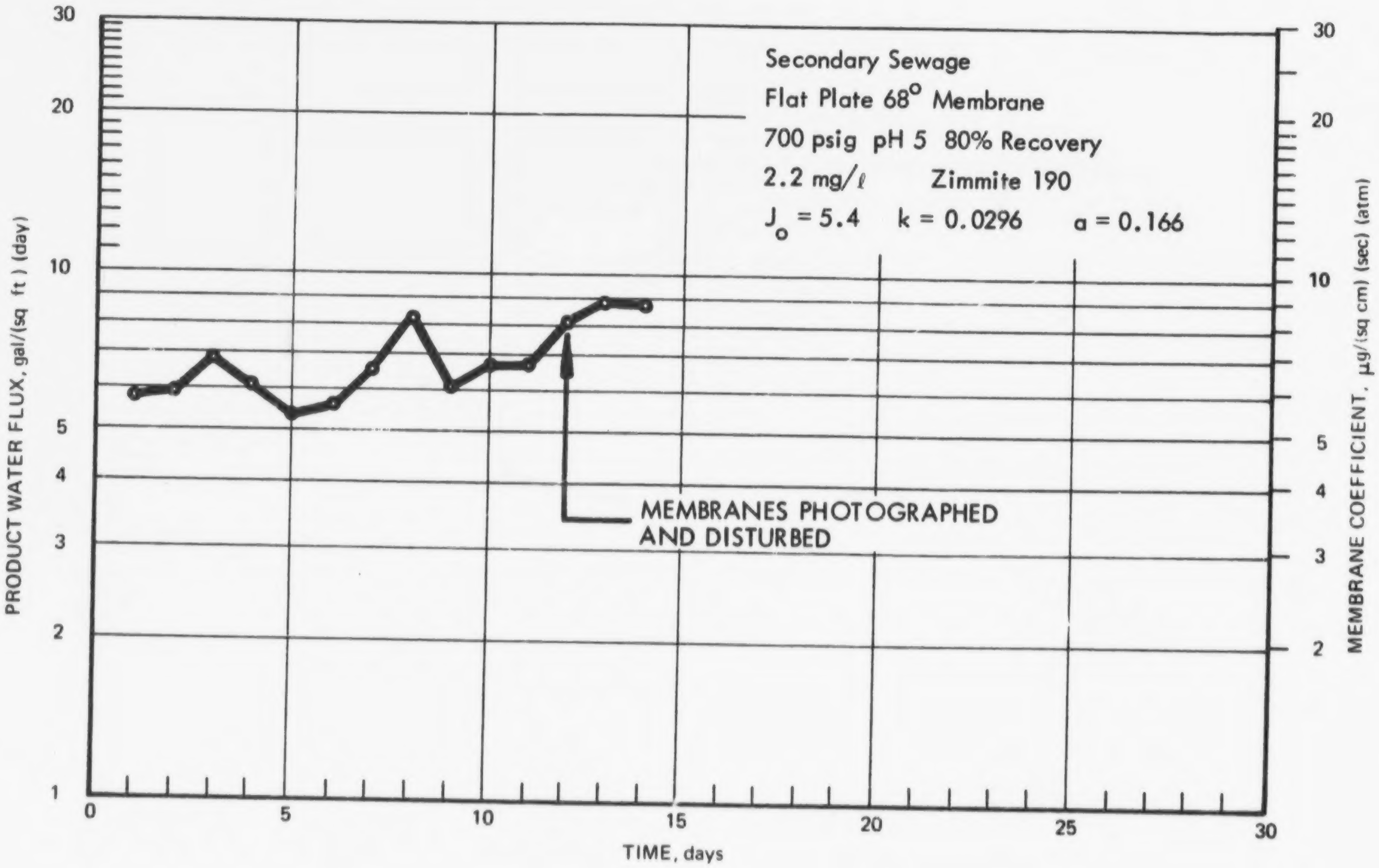

Figure 20. PRODUCT WATER FLUX, TEST 26

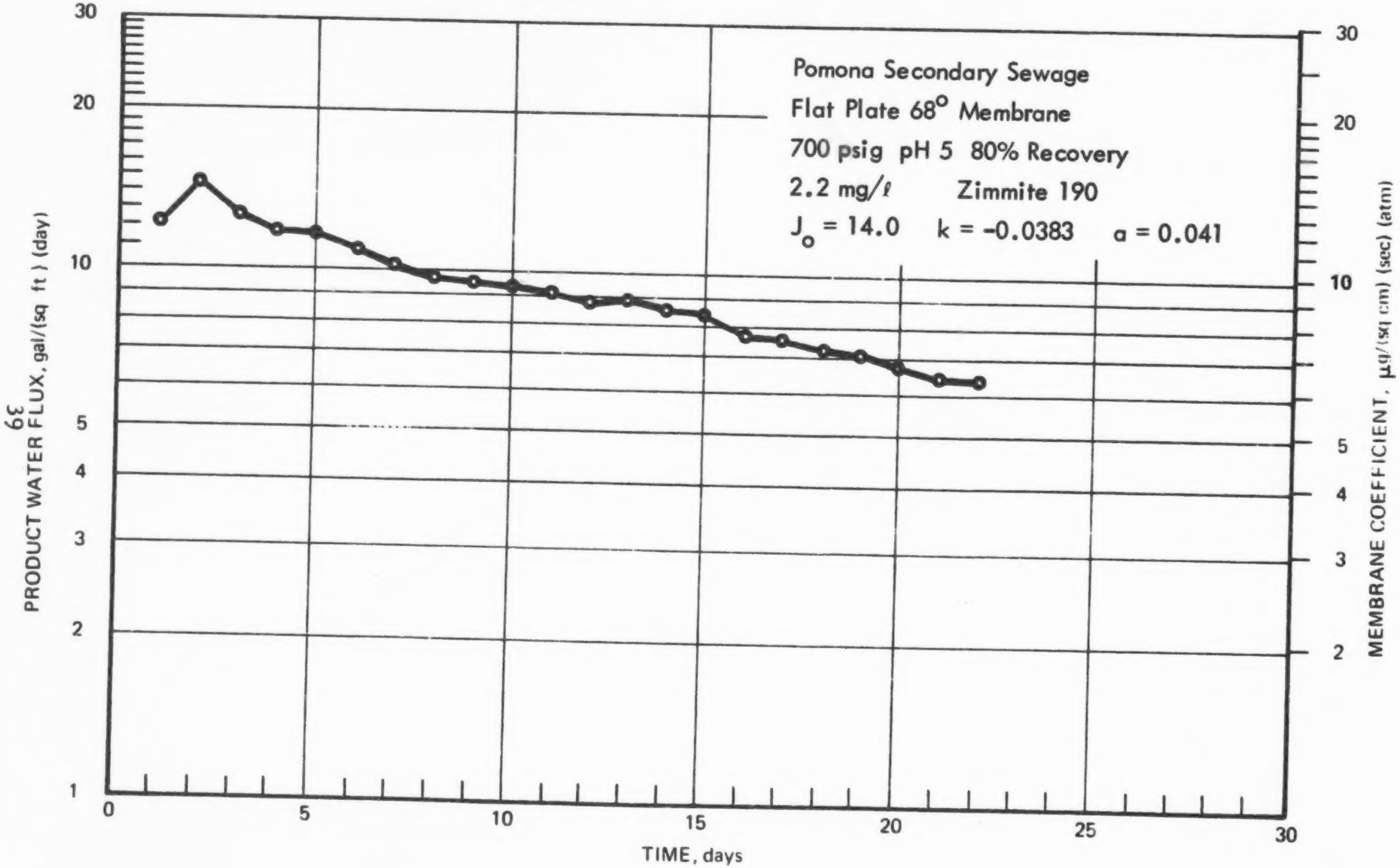

Figure 21. PRODUCT WATER FLUX, TEST 84

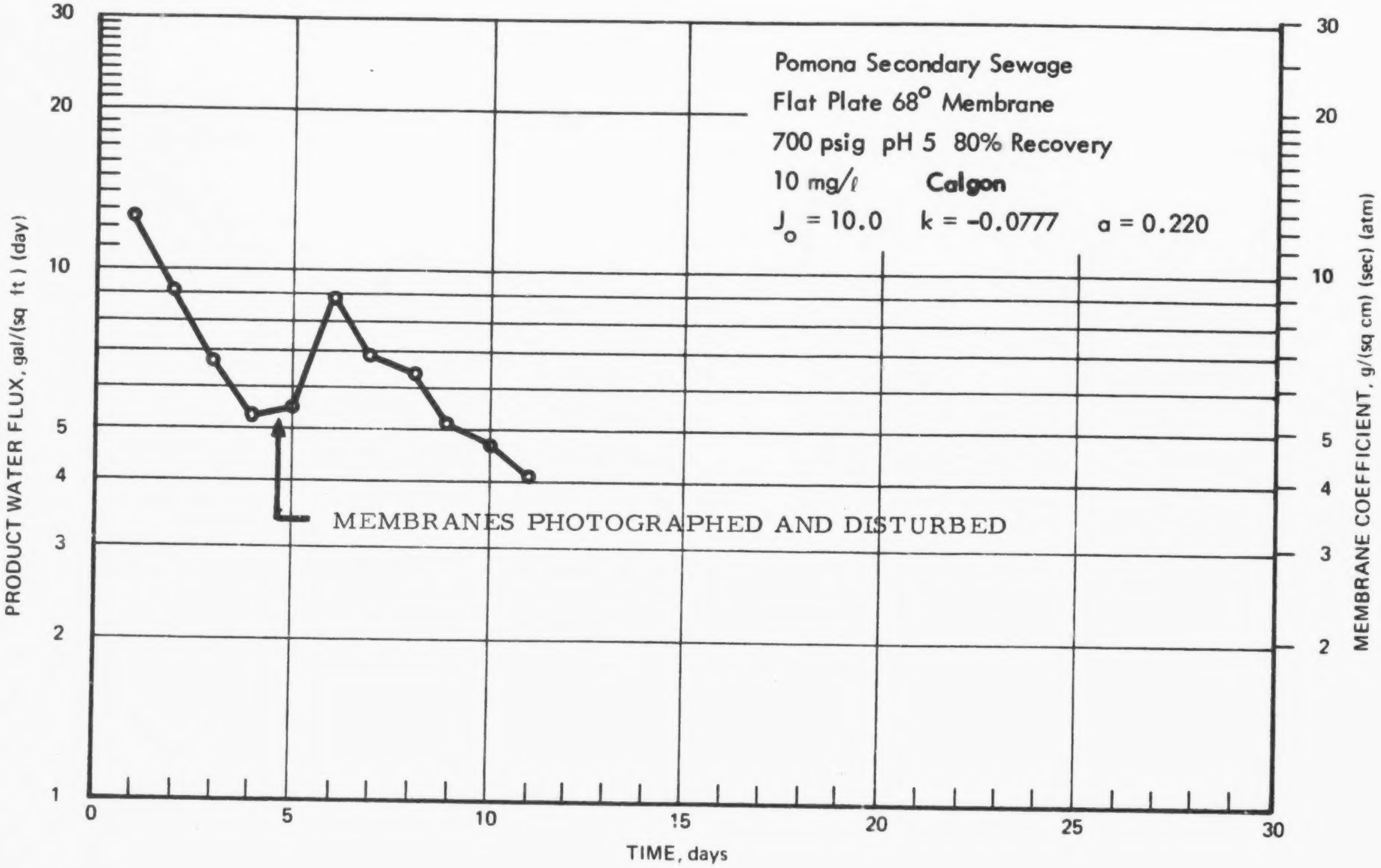

Figure 22. PRODUCT WATER FLUX, TEST 12

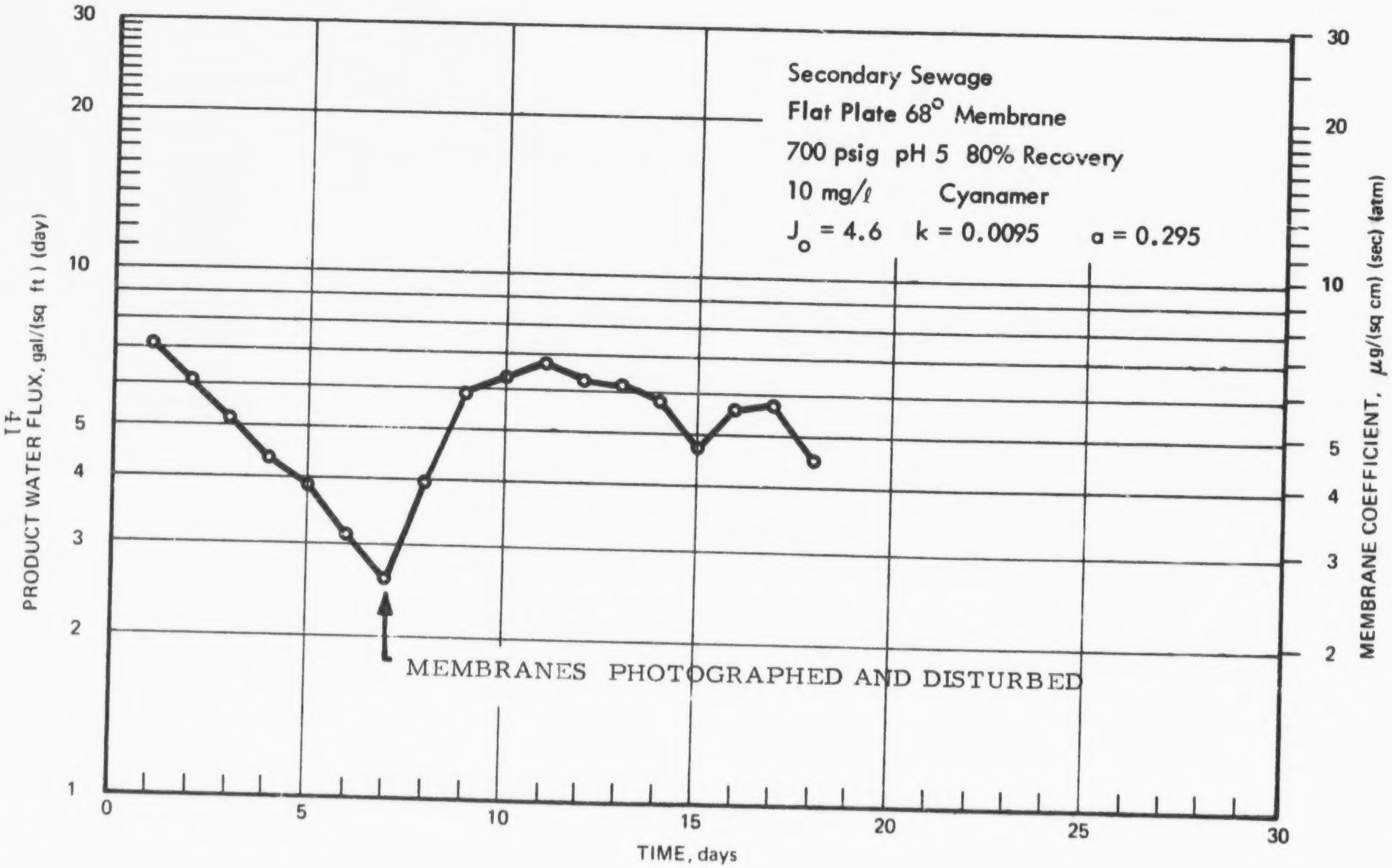

Figure 23. PRODUCT WATER FLUX, TEST 13

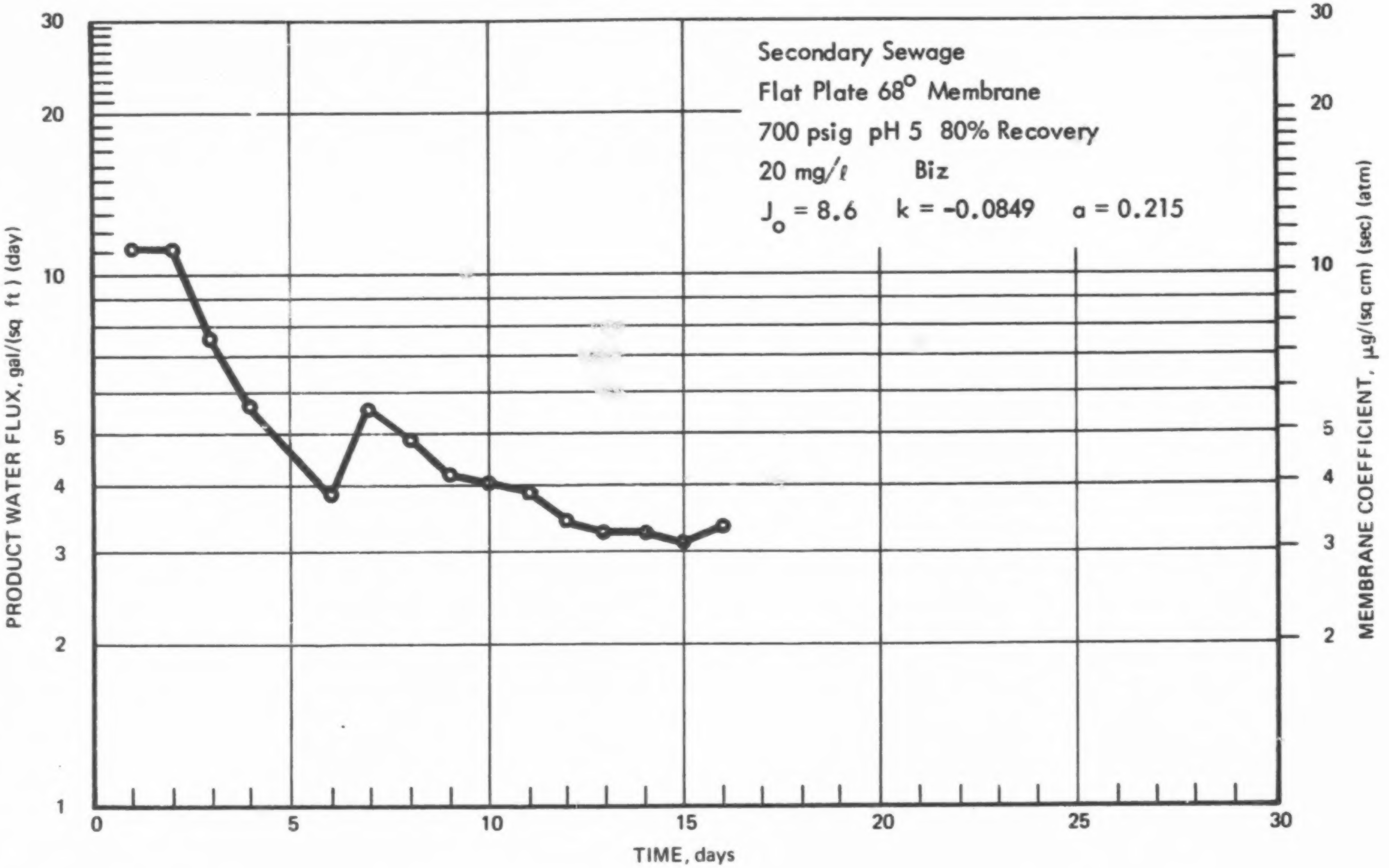

Figure 24. PRODUCT WATER FLUX, TEST 41

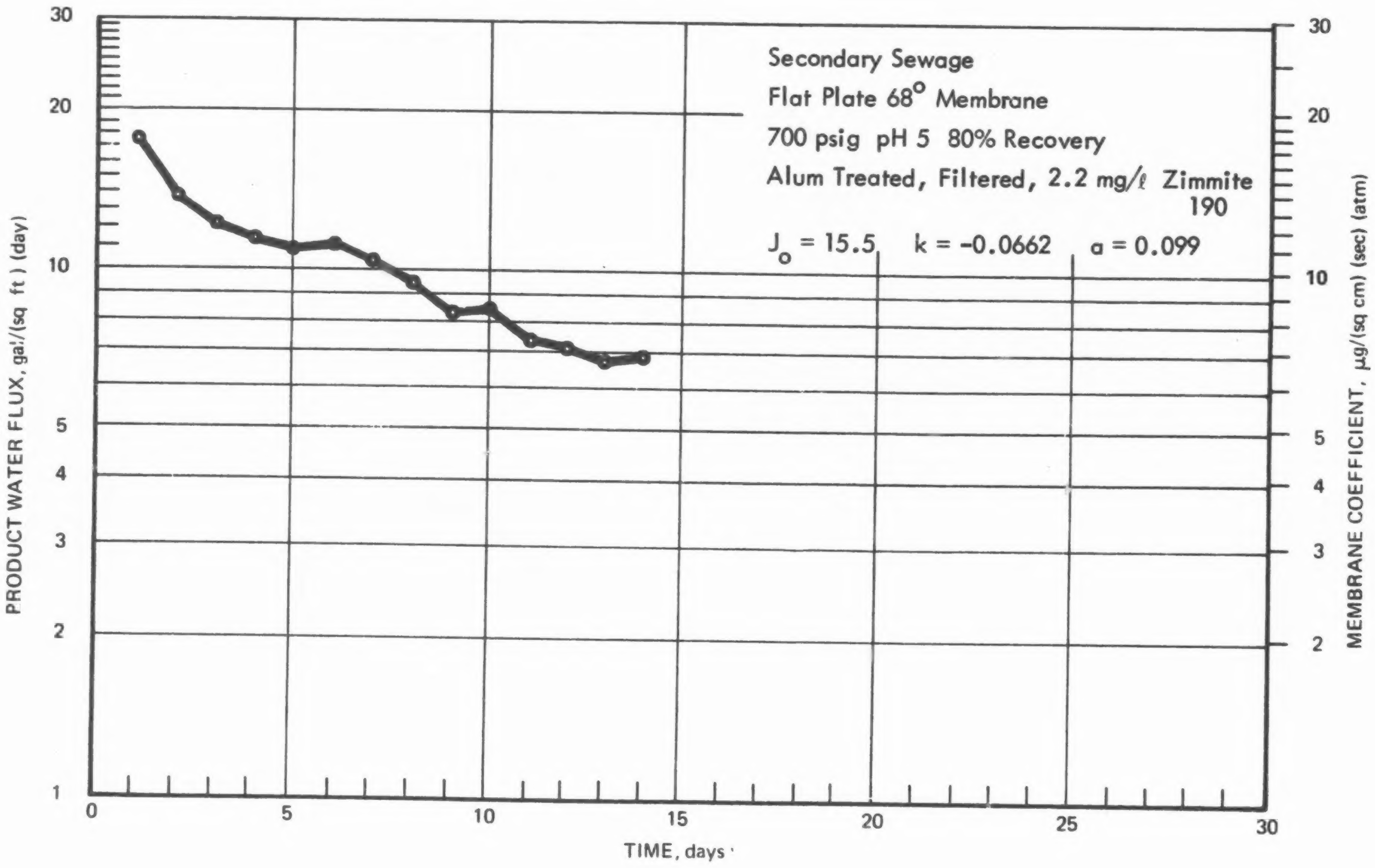

Figure 25. PRODUCT WATER FLUX, TEST 34

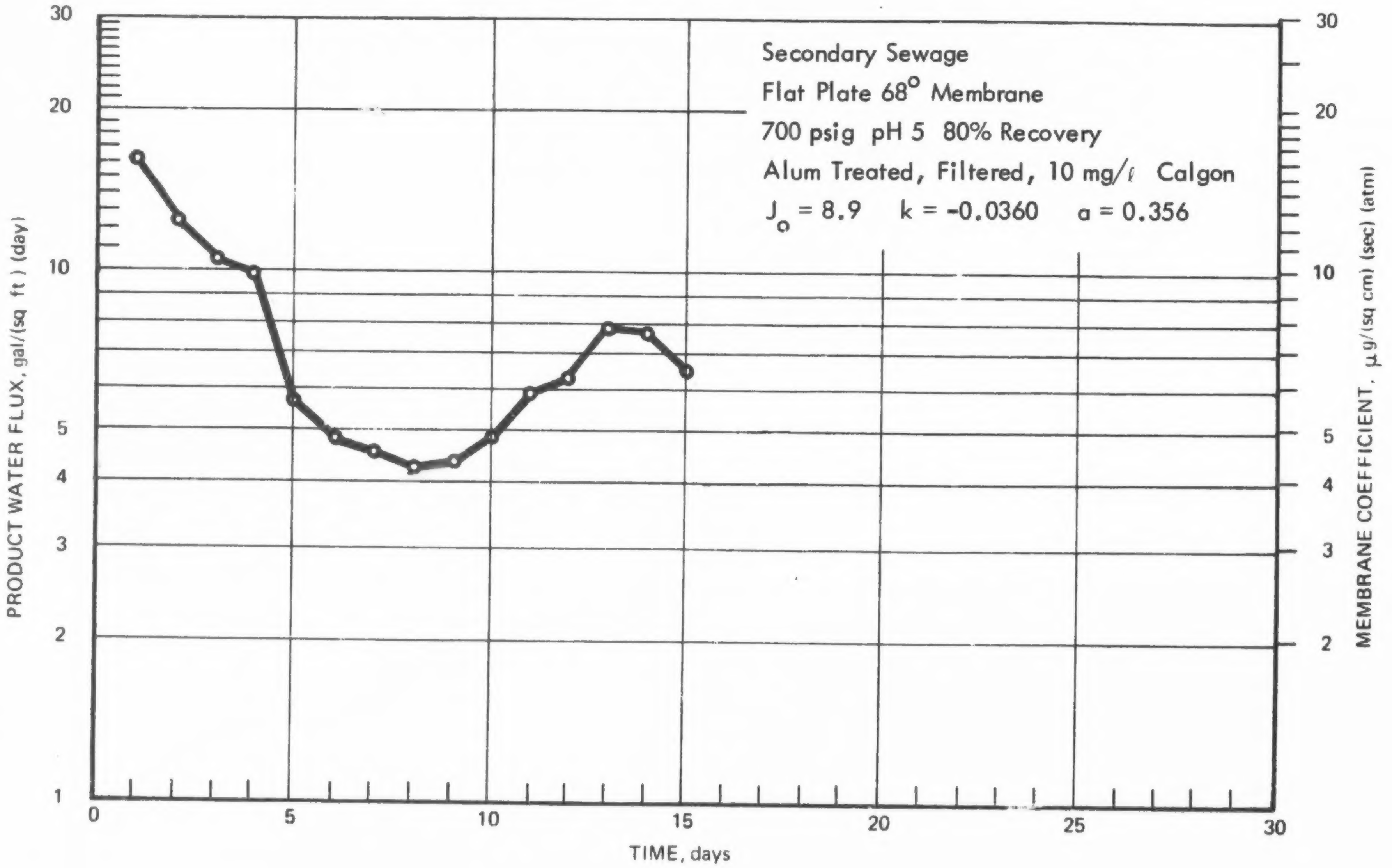

Figure 26. PRODUCT WATER FLUX, TEST 38

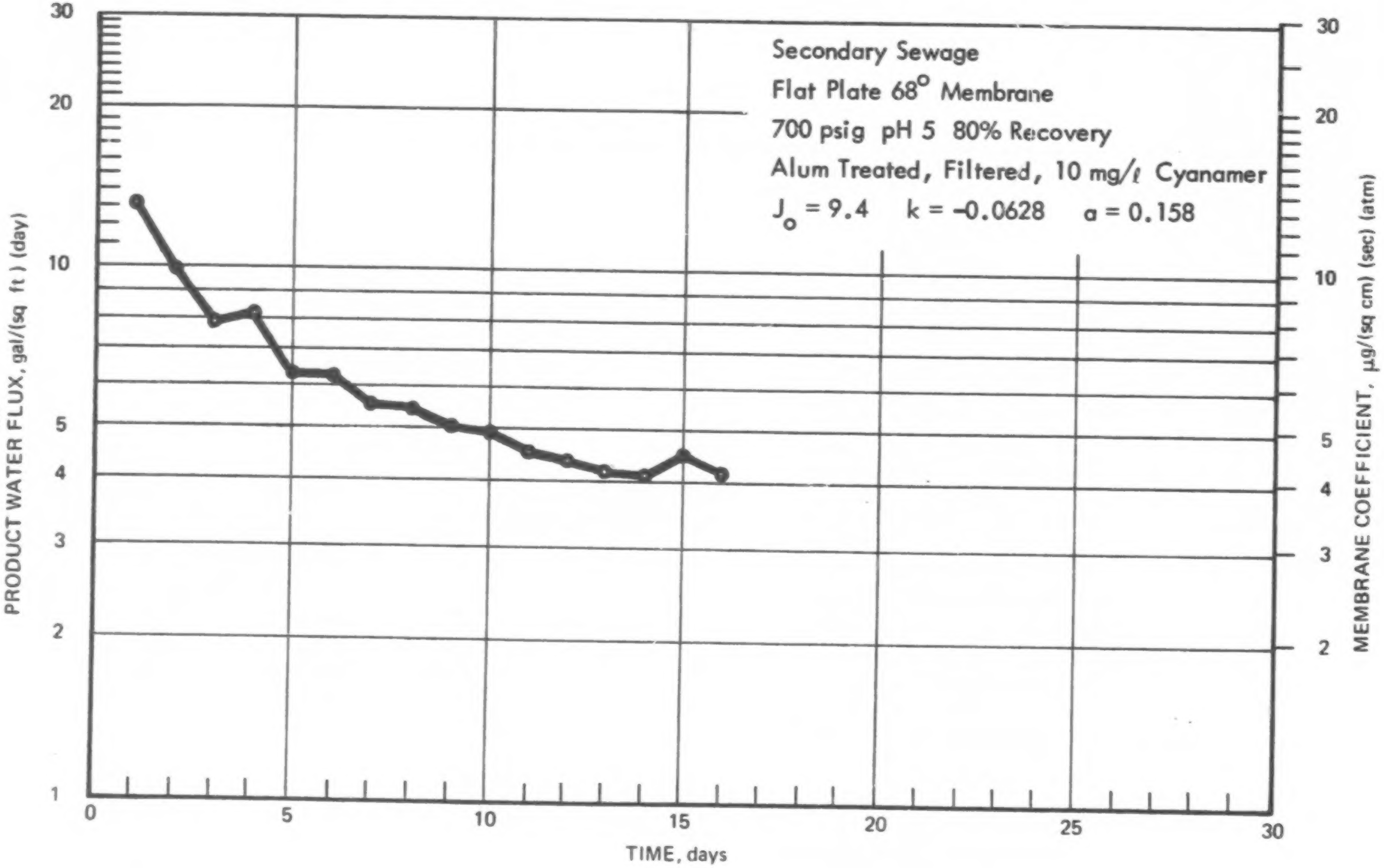

Figure 27. PRODUCT WATER FLUX, TEST 33

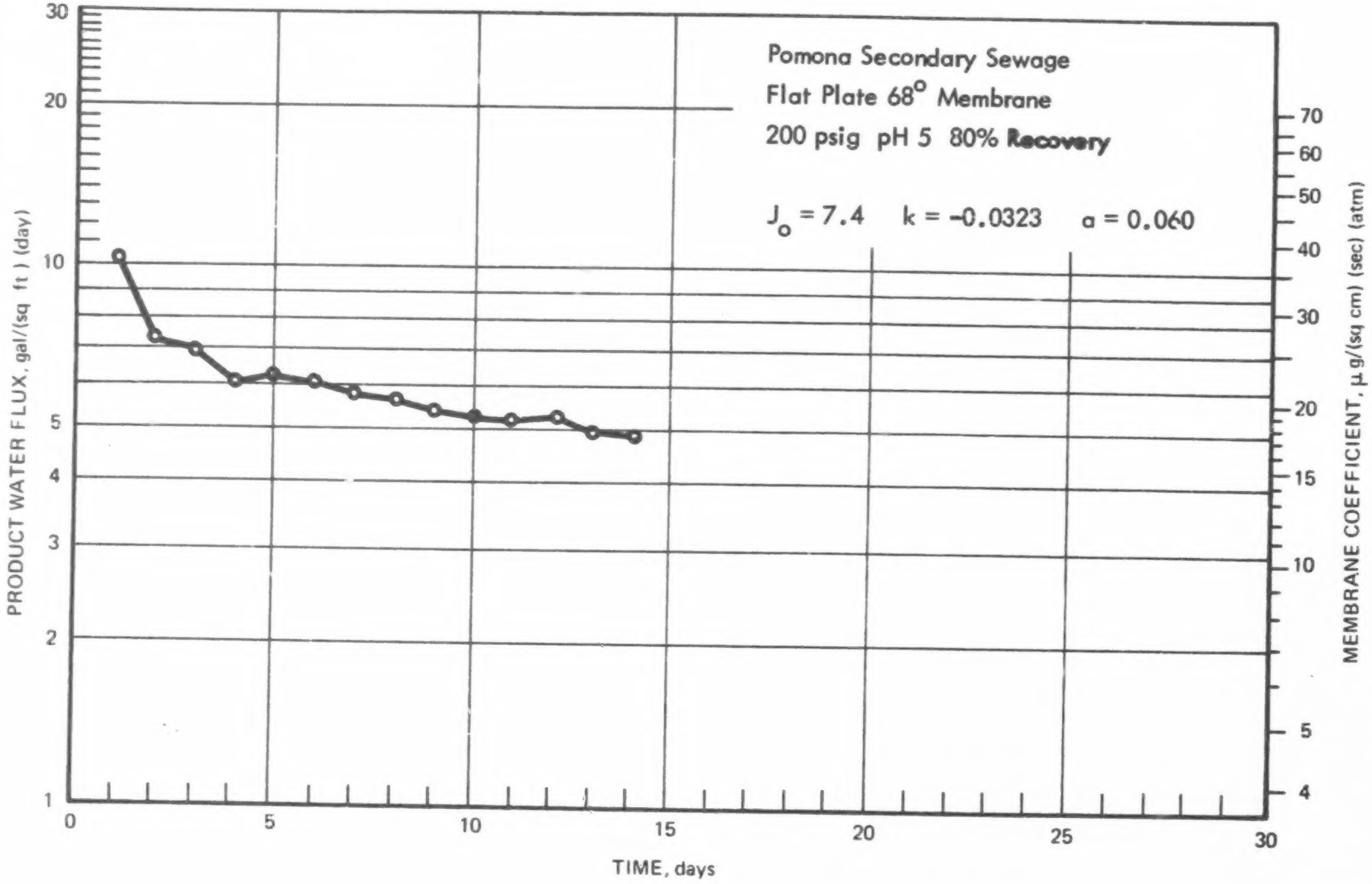

Figure 28. PRODUCT WATER FLUX, TEST 11

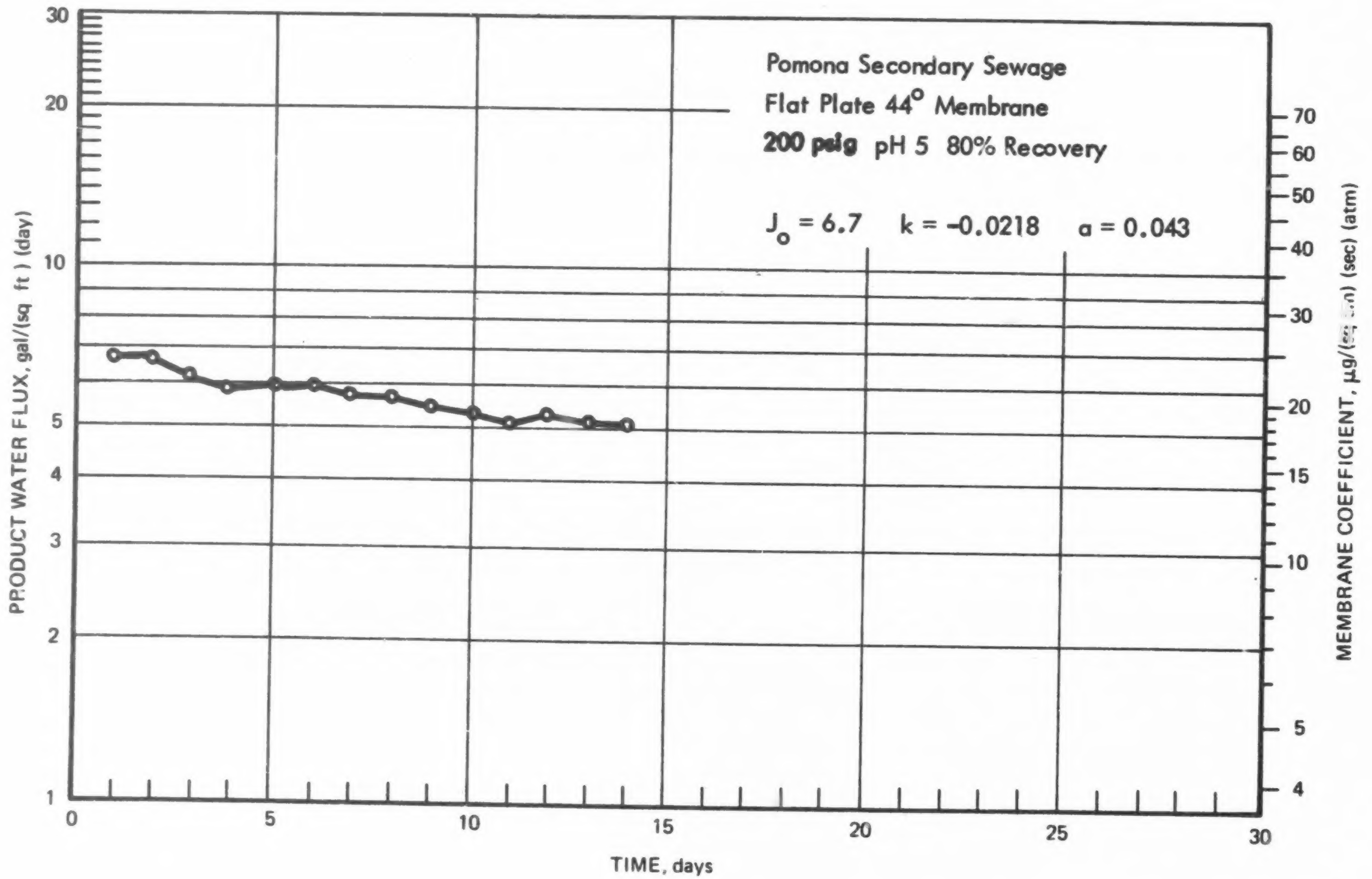

Figure 29. PRODUCT WATER FLUX, TEST 10

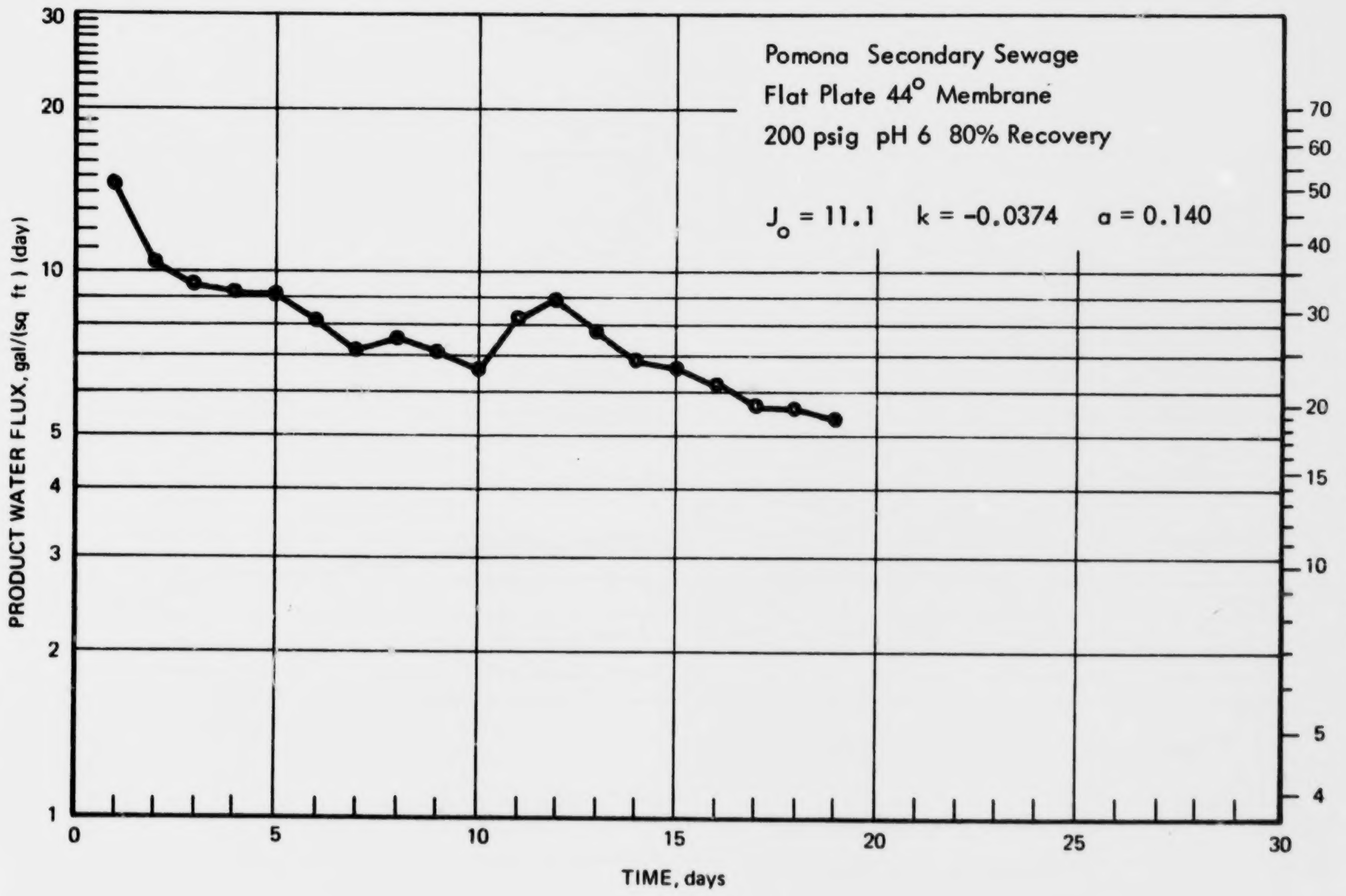

Figure 30. PRODUCT WATER FLUX, TEST 90

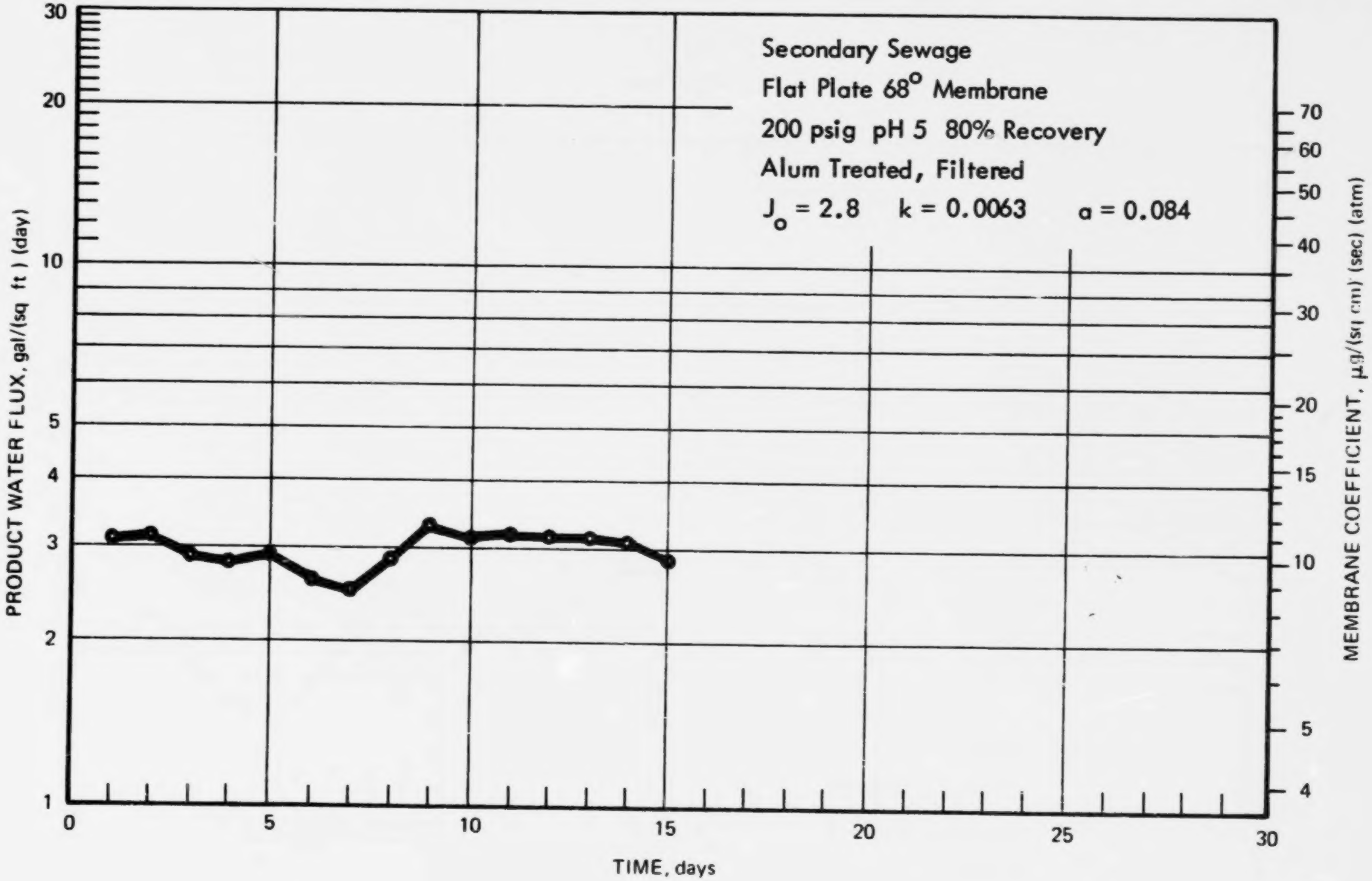

Figure 31. PRODUCT WATER FLUX, TEST 31

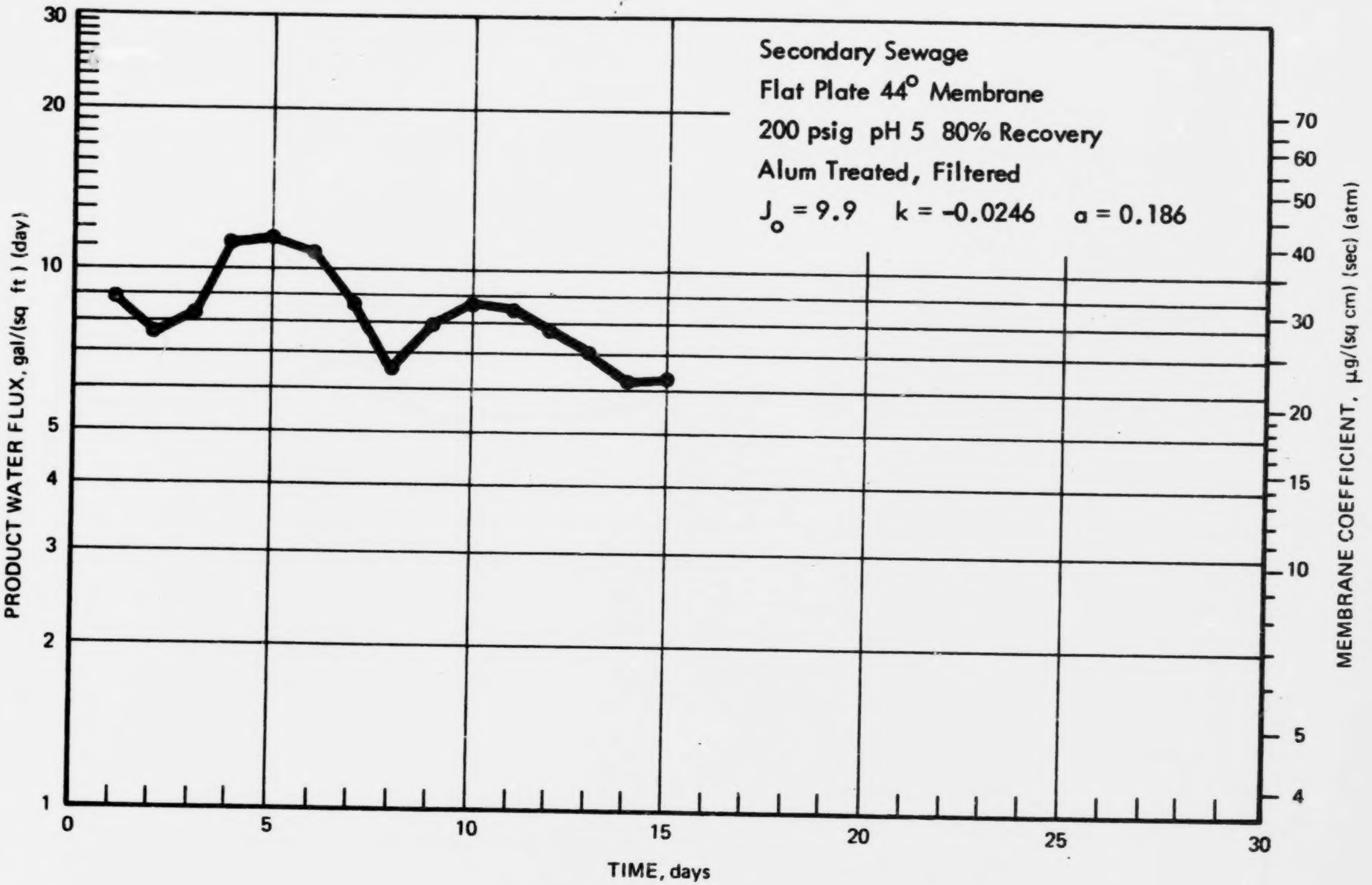

Figure 32. PRODUCT WATER FLUX, TEST 32

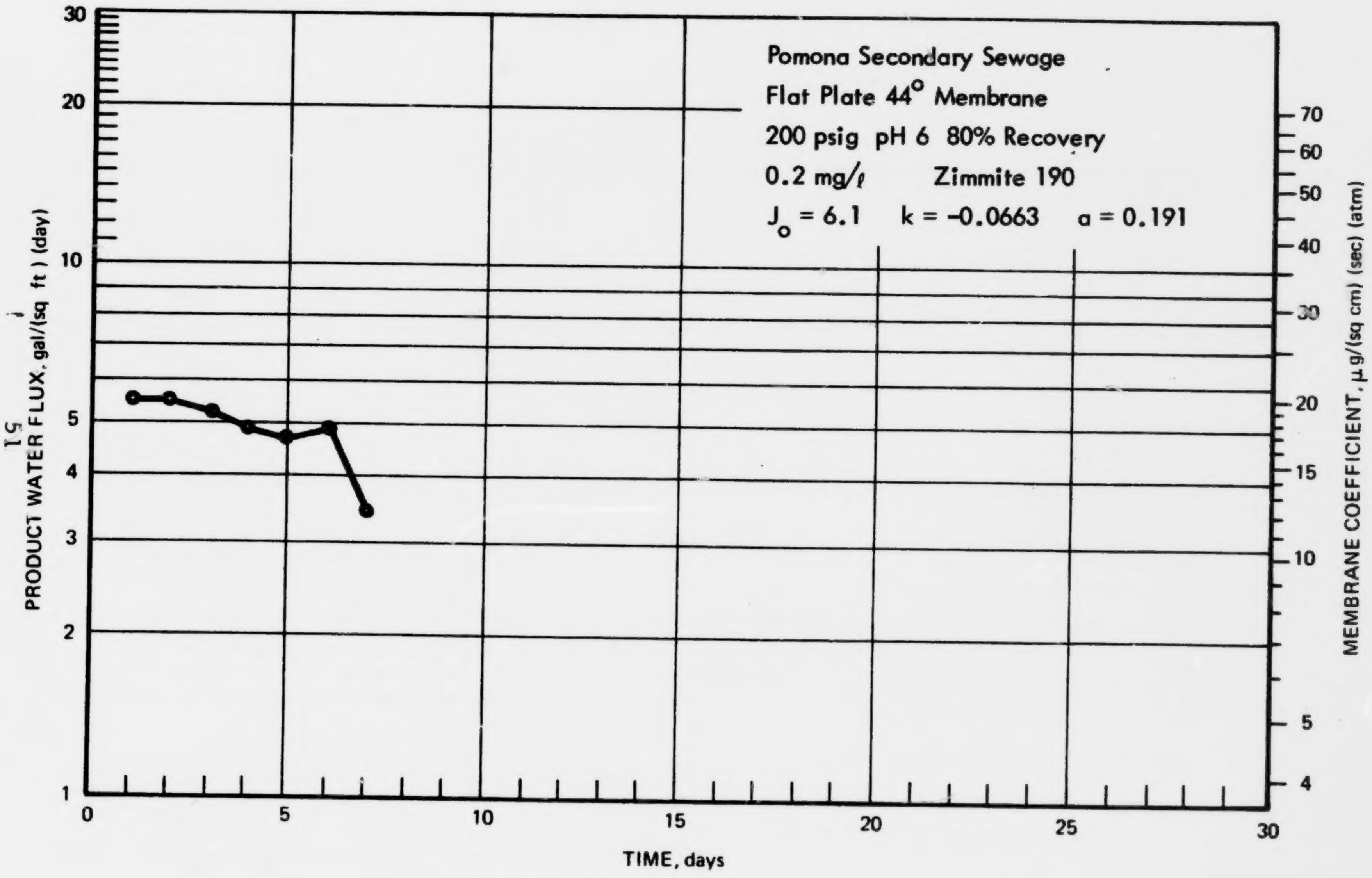

Figure 33. PRODUCT WATER FLUX, TEST 94

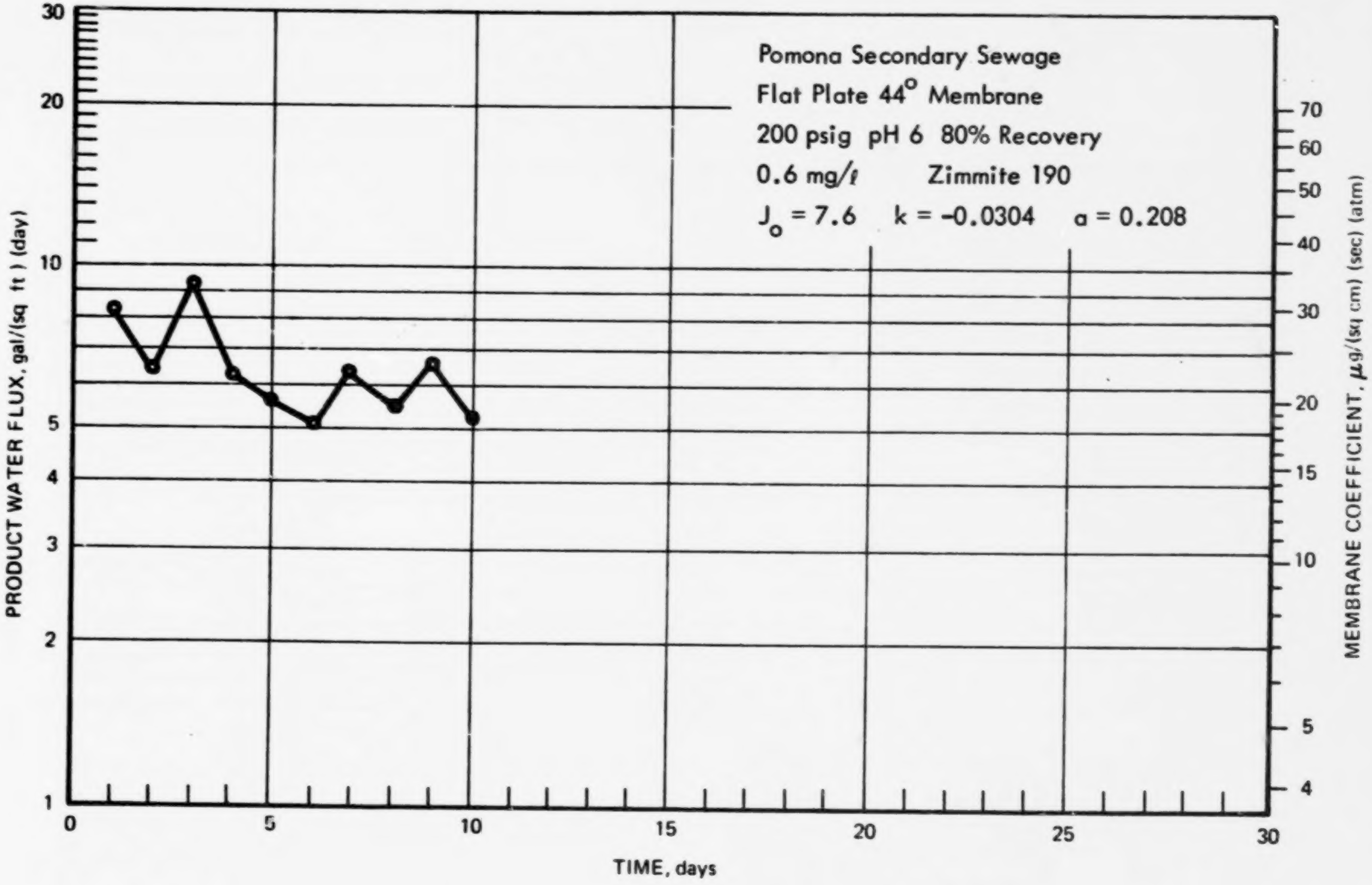

Figure 34. PRODUCT WATER FLUX, TEST 93

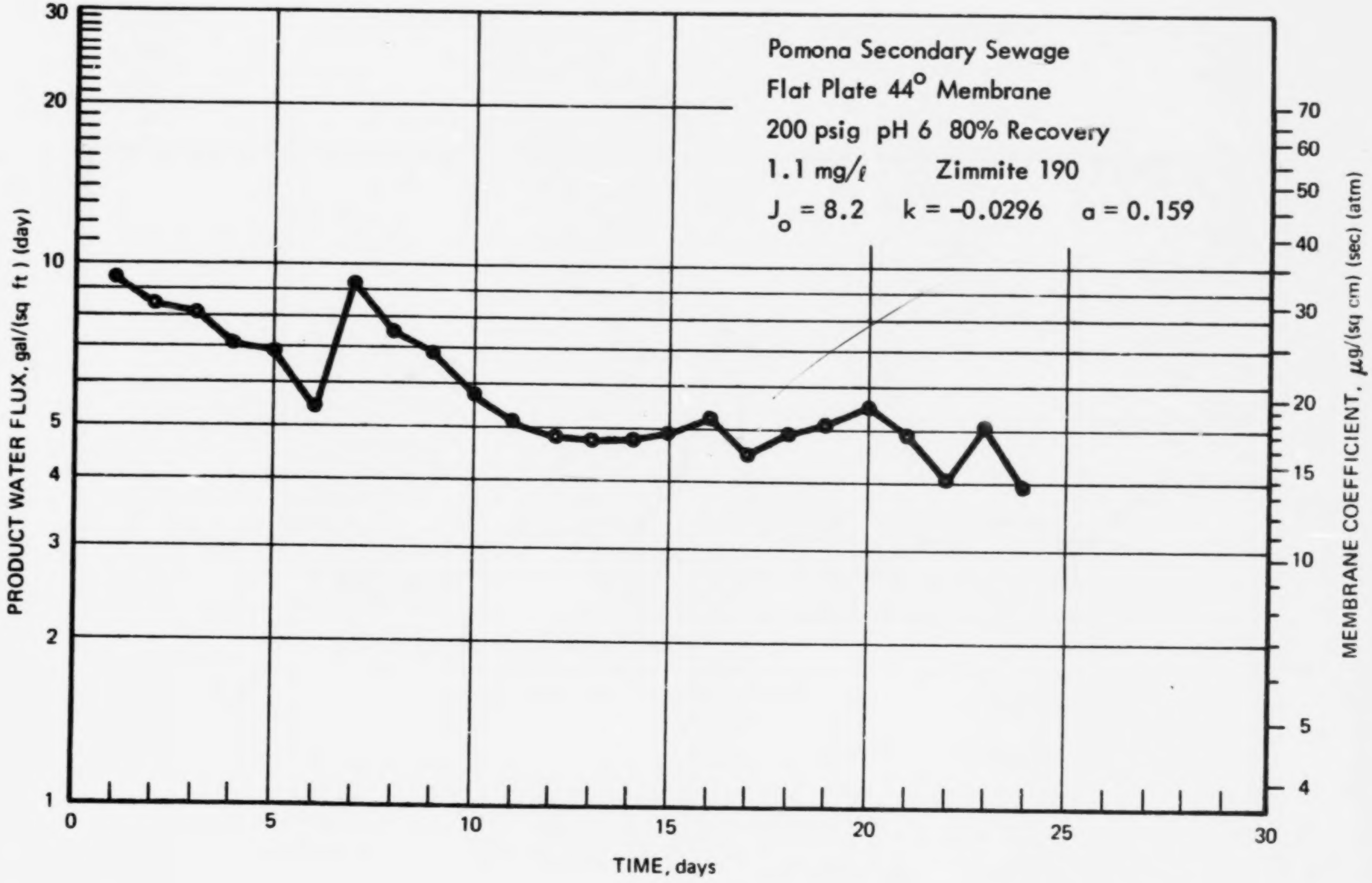

Figure 35. PRODUCT WATER FLUX, TEST 88

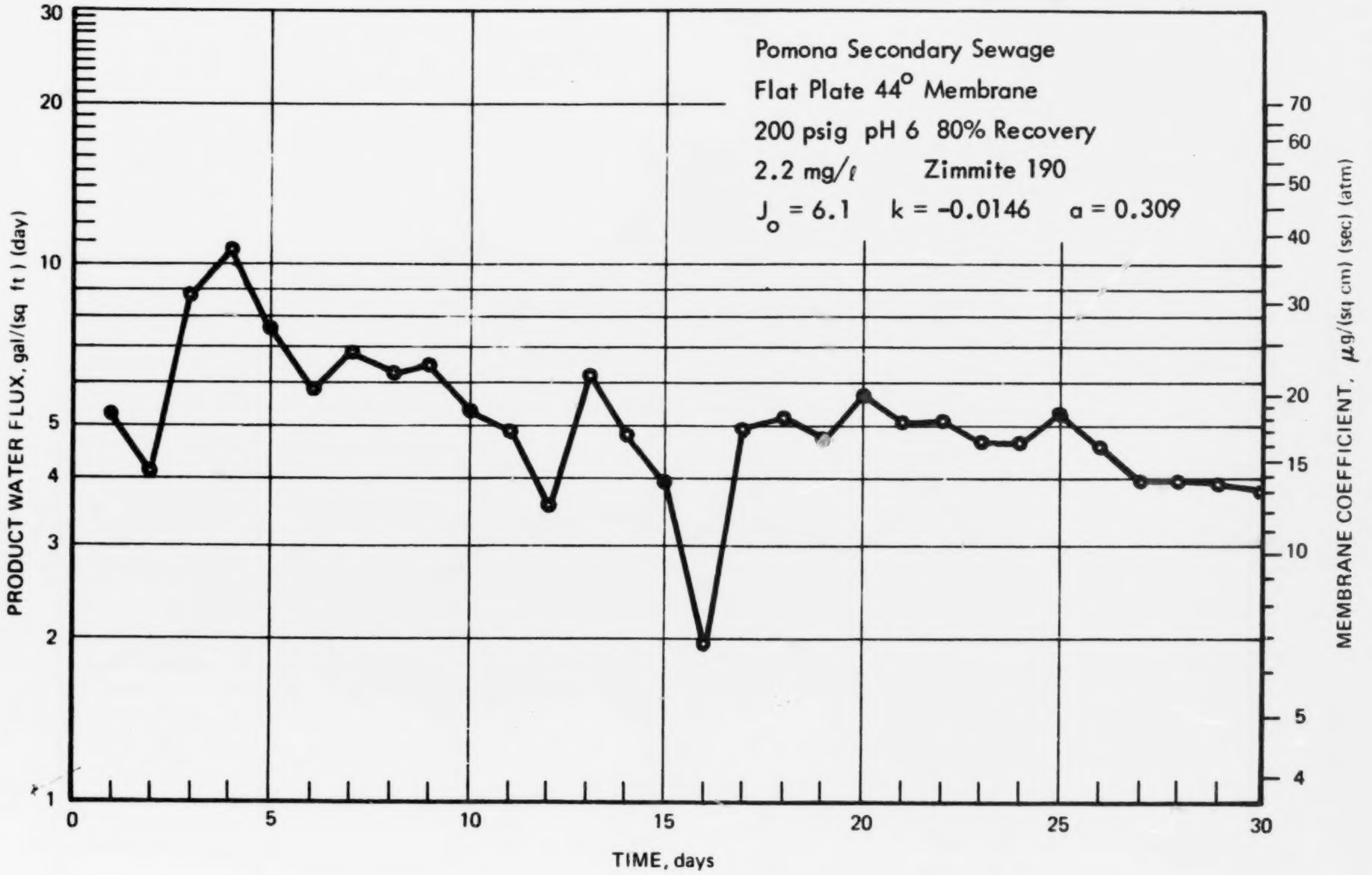

Figure 36. PRODUCT WATER FLUX, TEST 87

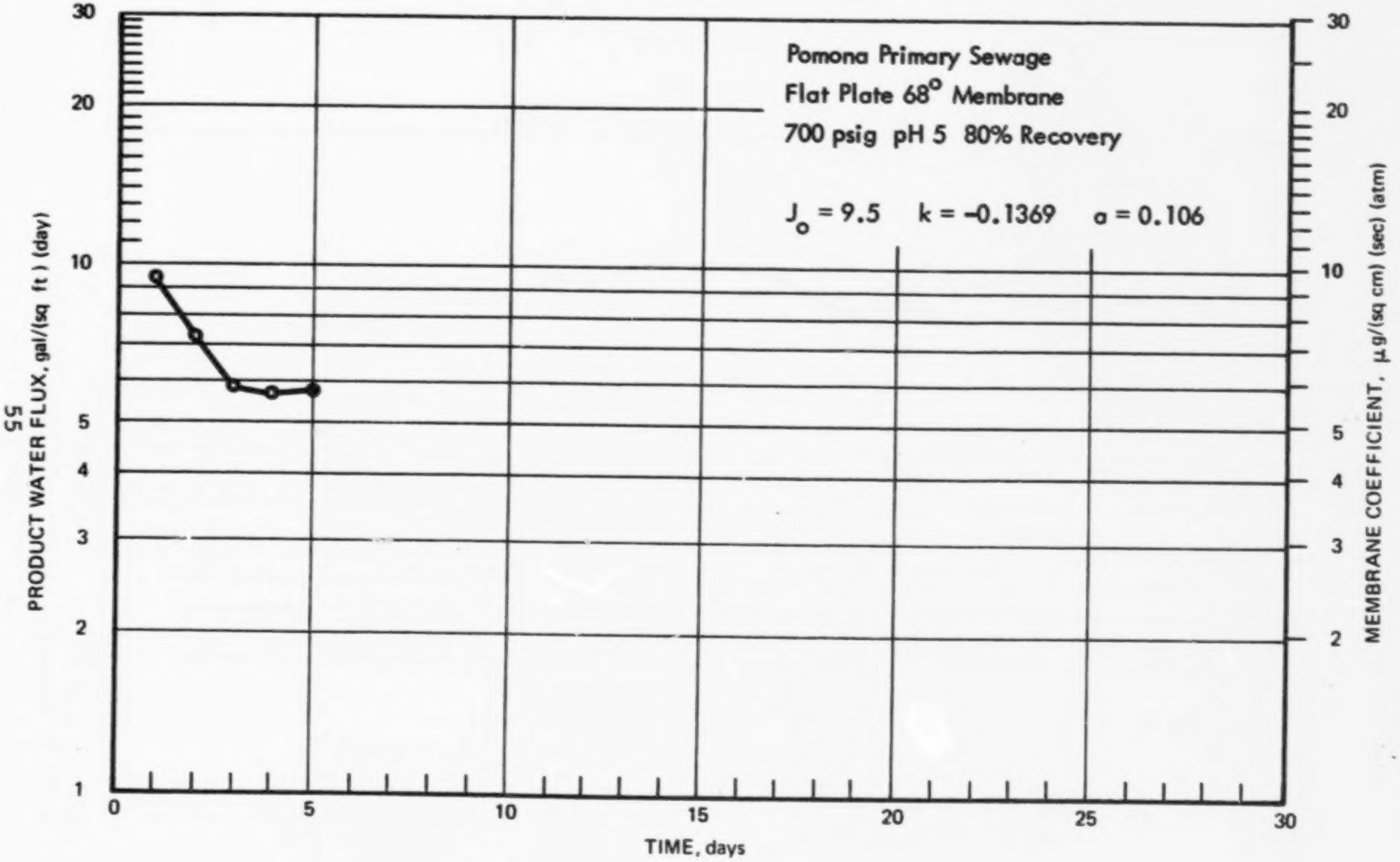

Figure 37. PRODUCT WATER FLUX, TEST 16

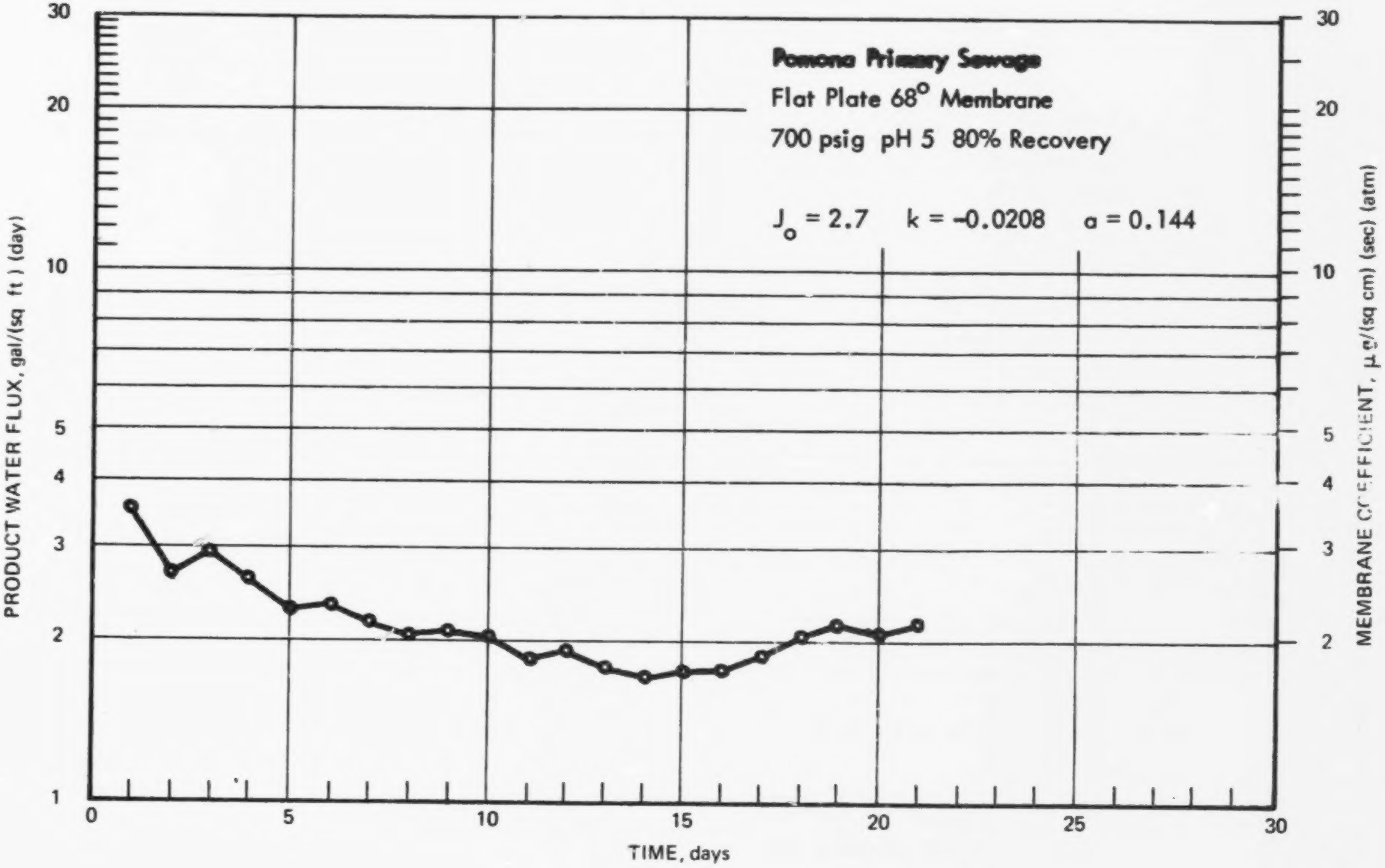

Figure 38. PRODUCT WATER FLUX, TEST 66

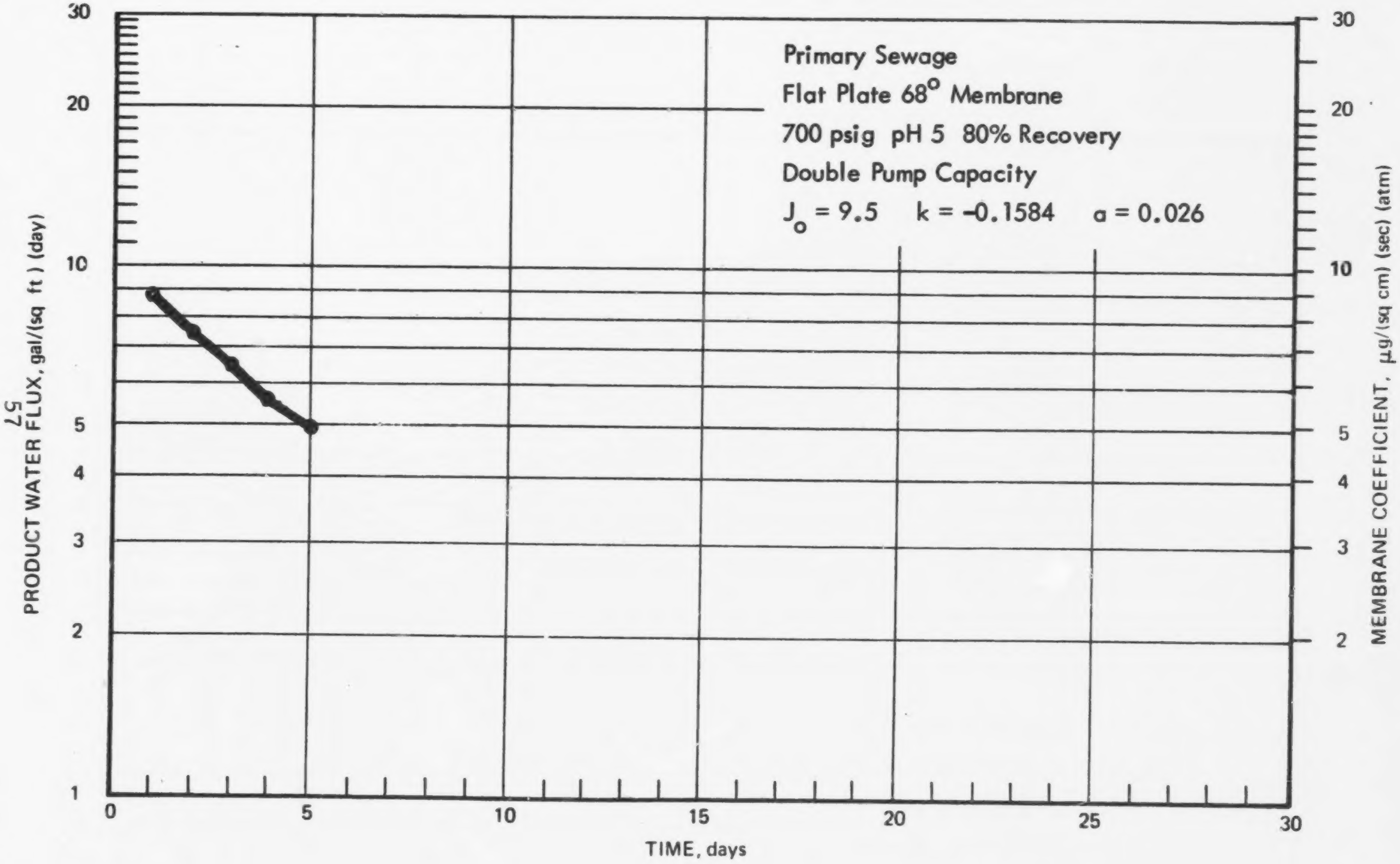

Figure 39. PRODUCT WATER FLUX, TEST 22

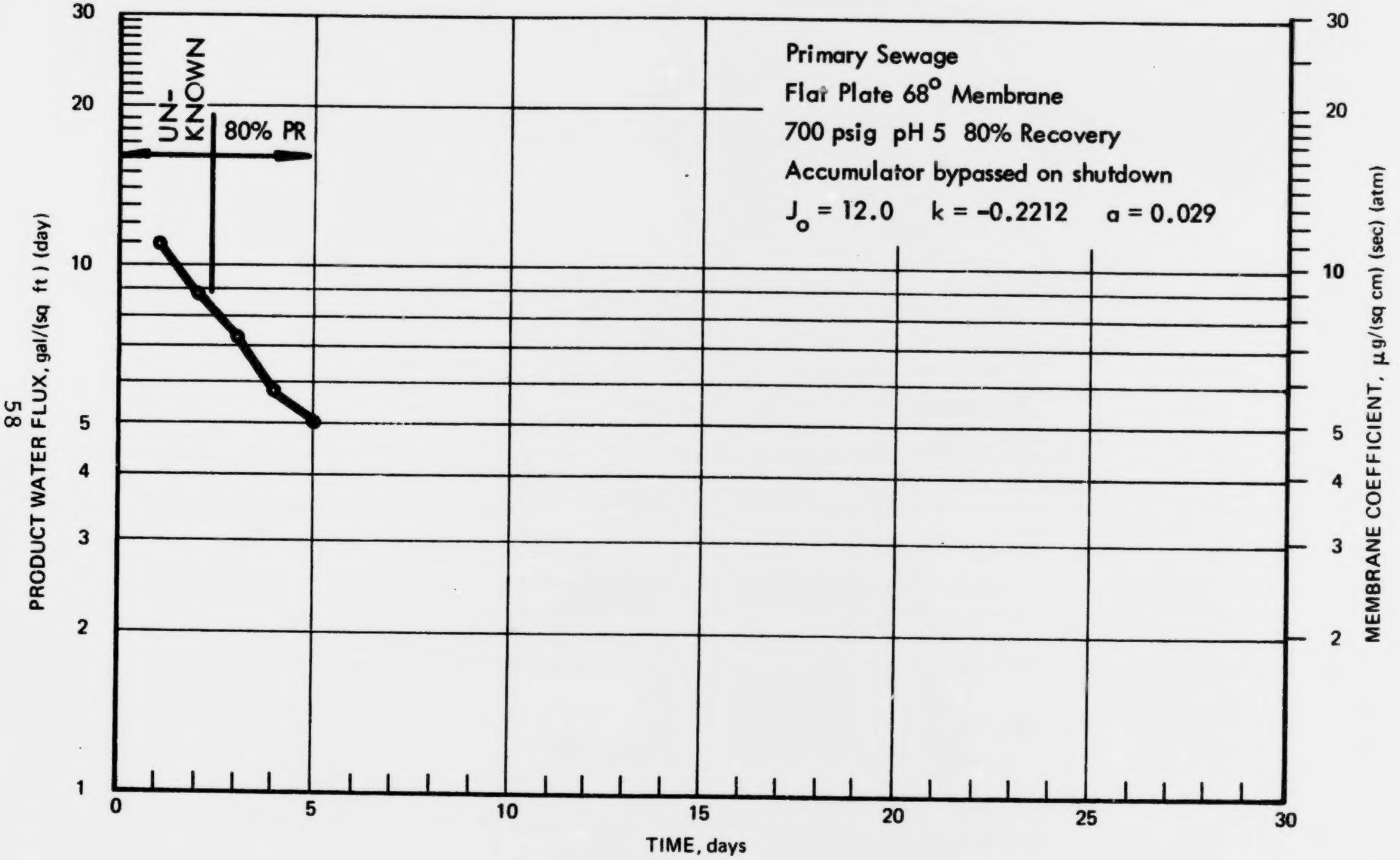

Figure 40. PRODUCT WATER FLUX, TEST 21

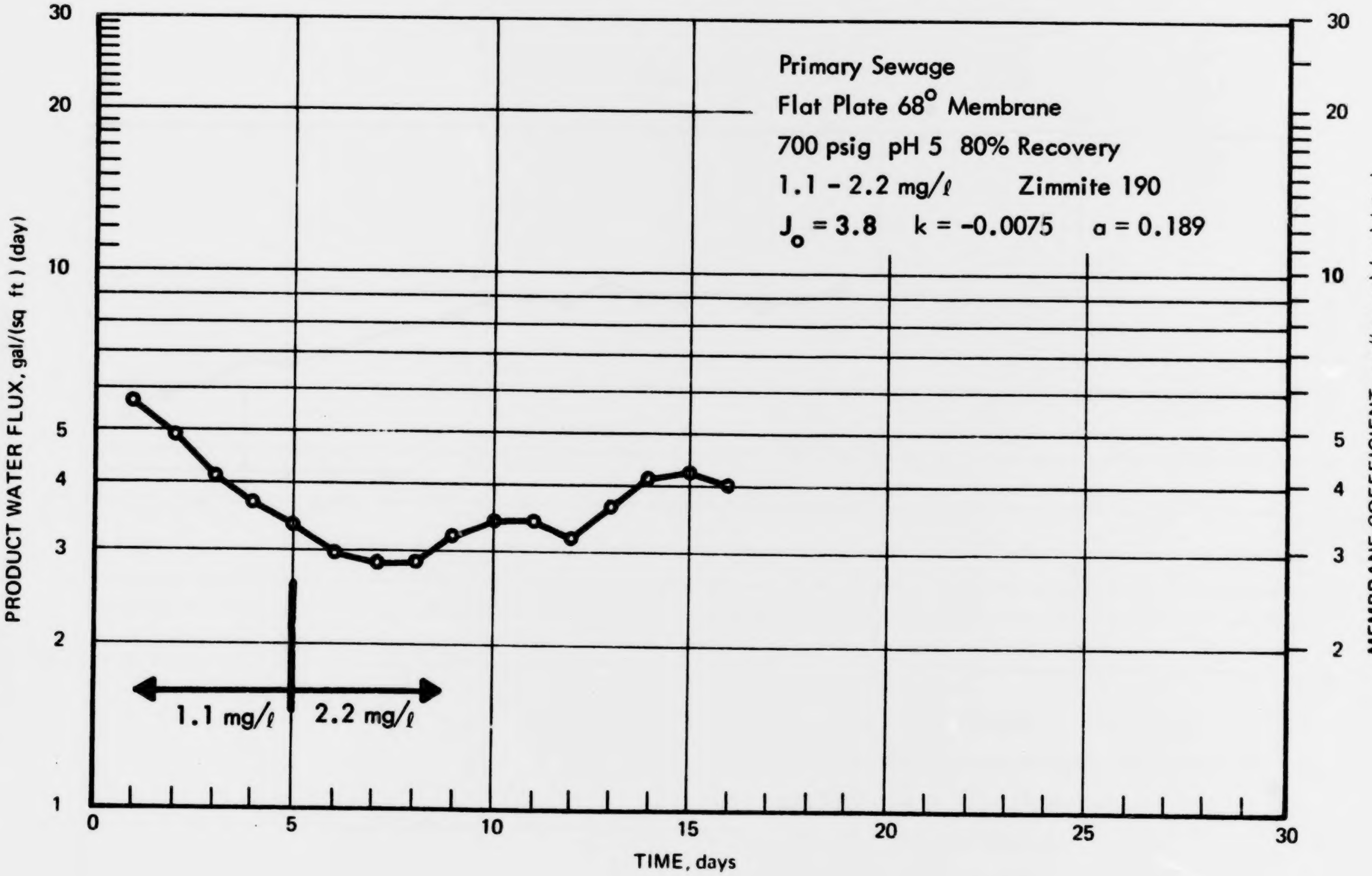

Figure 41. PRODUCT WATER FLUX, TEST 19

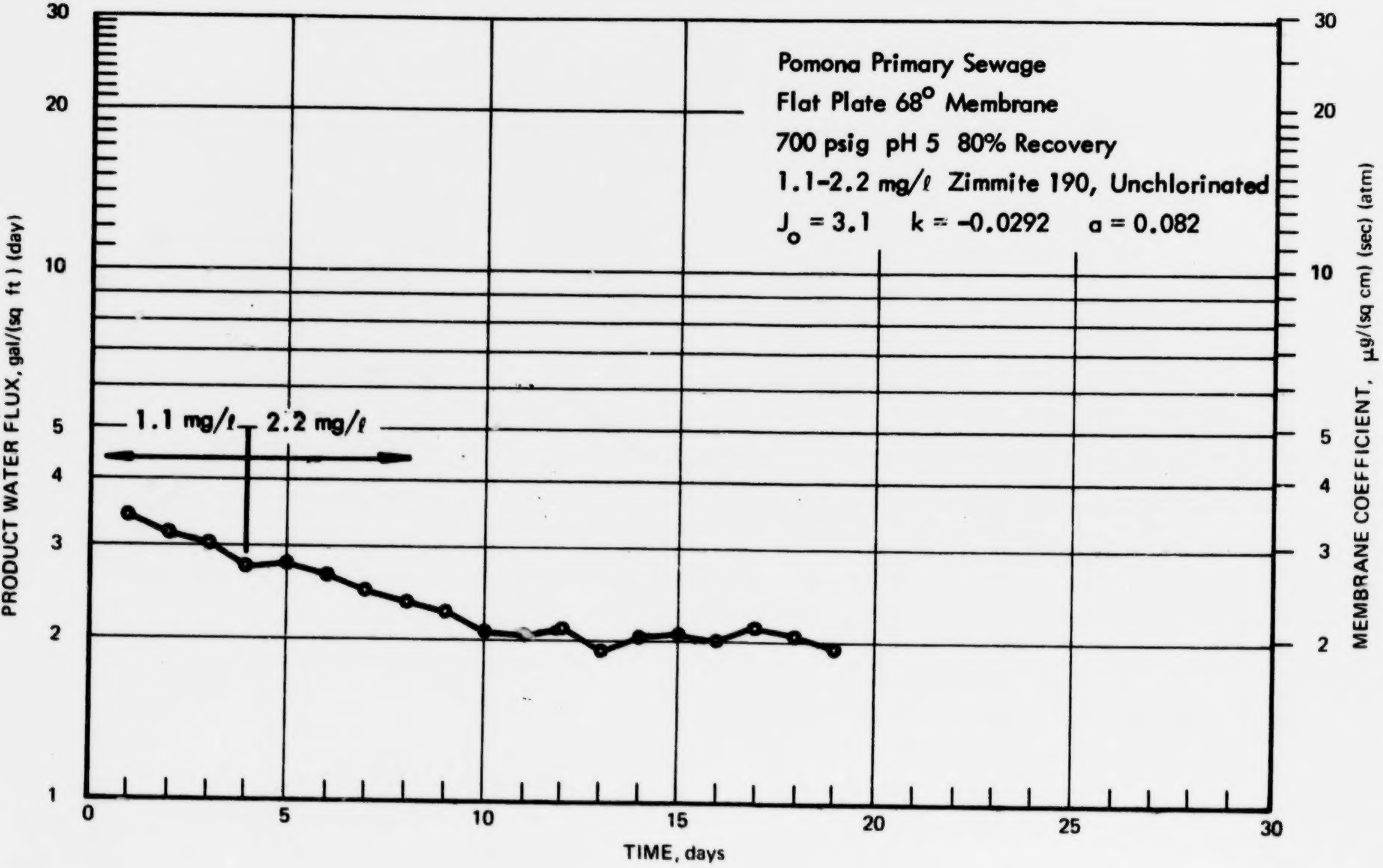

Figure 42. PRODUCT WATER FLUX, TEST 59

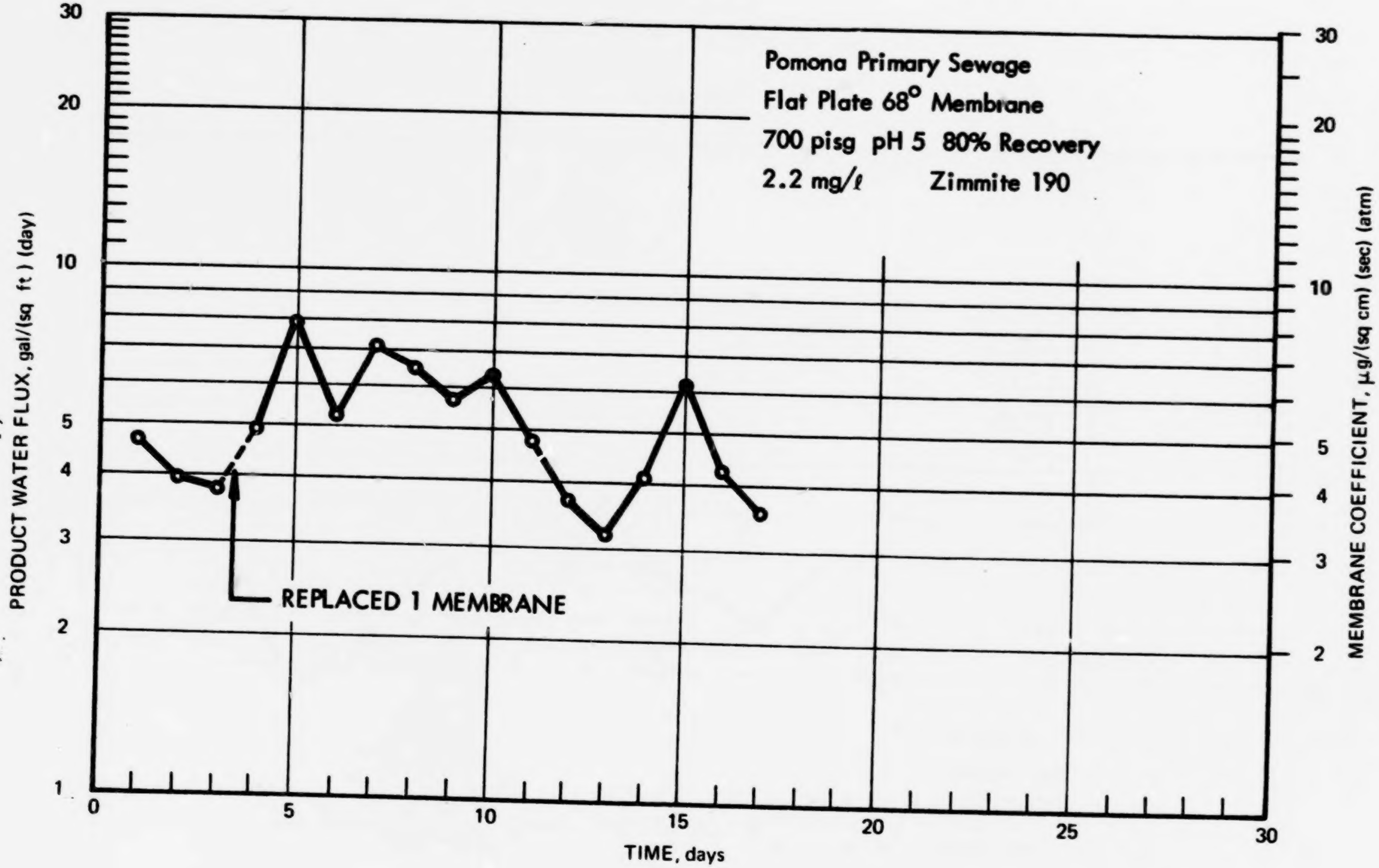

Figure 43. PRODUCT WATER FLUX, TEST 53

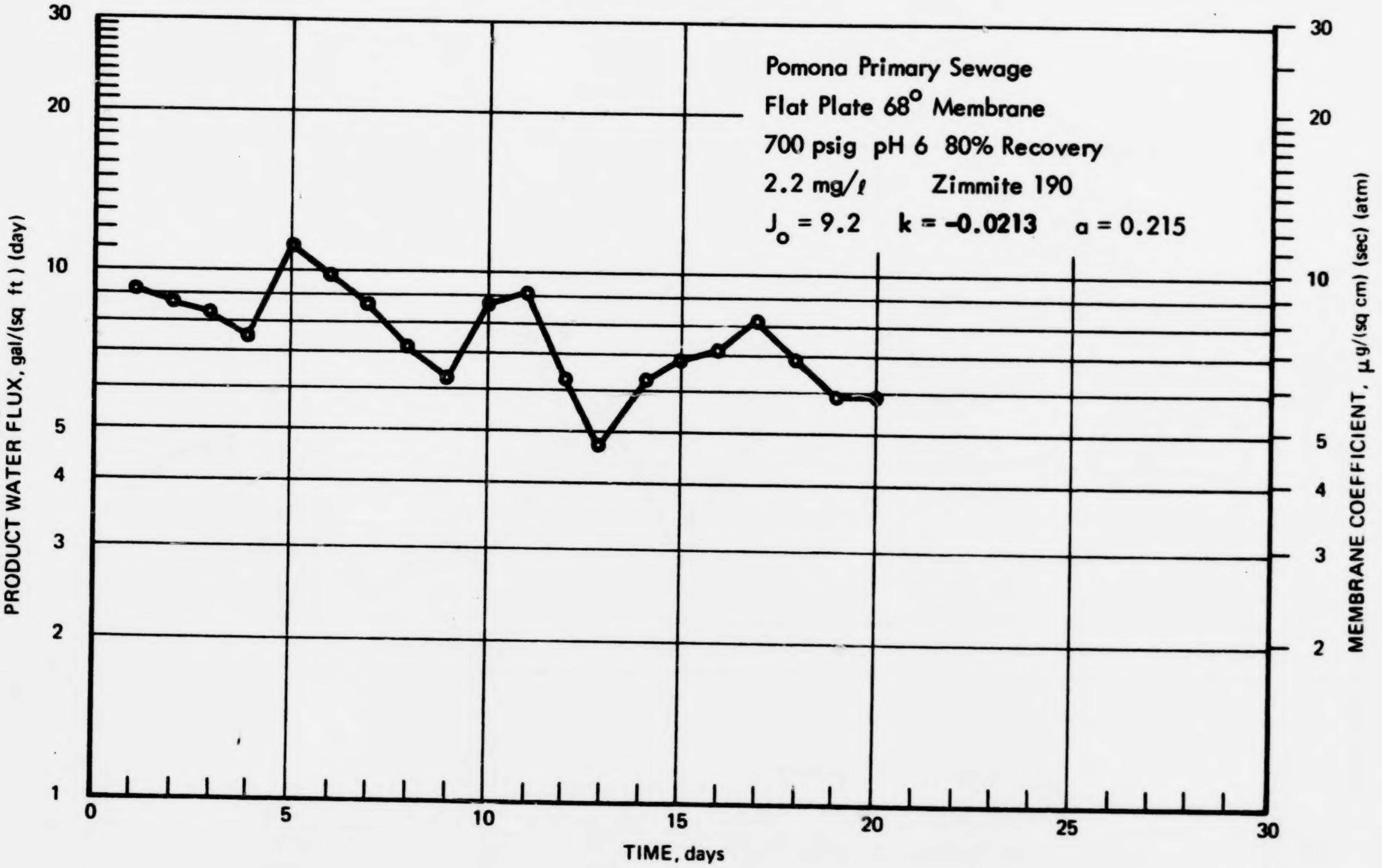

Figure 44. PRODUCT WATER FLUX, TEST 74

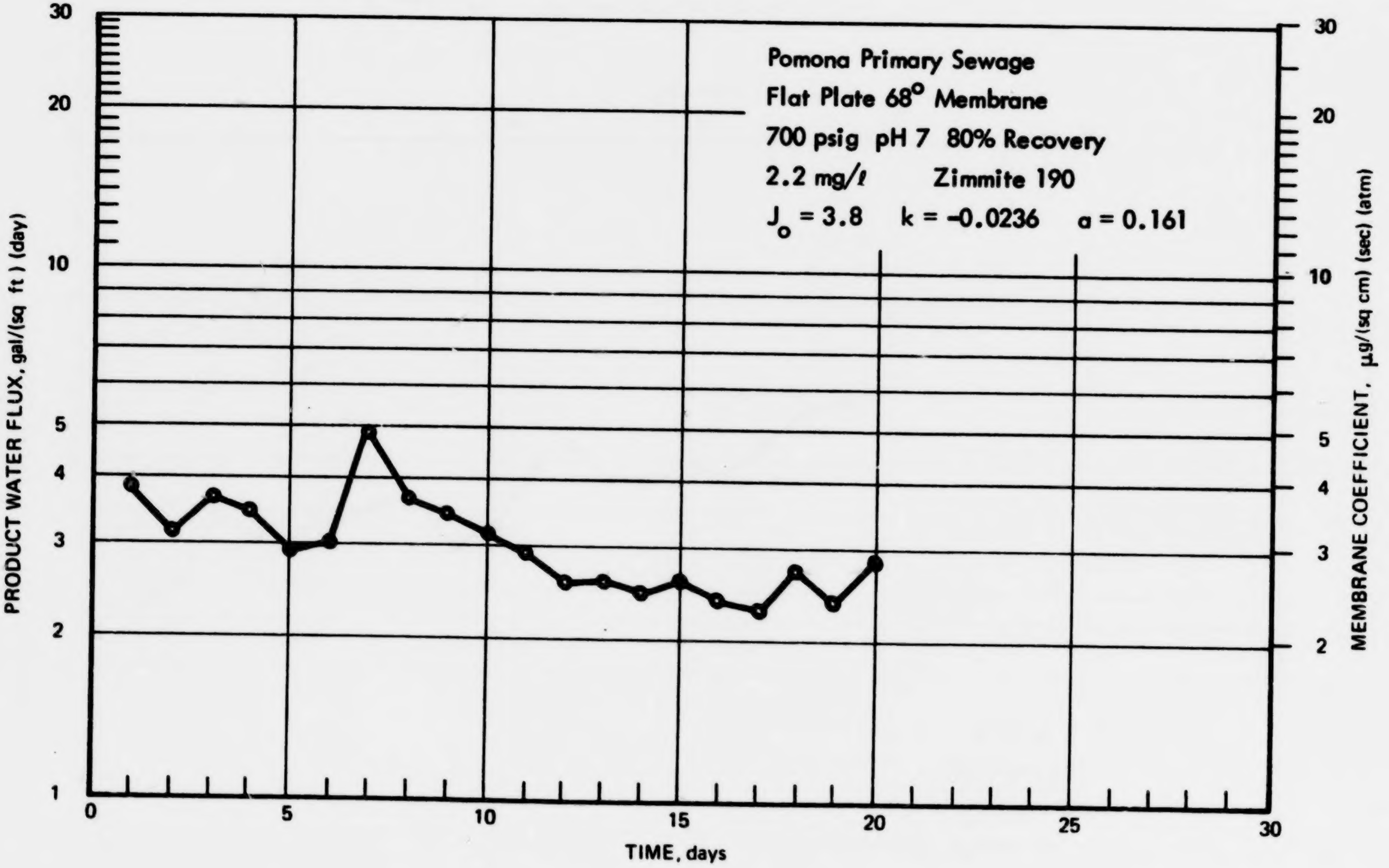

Figure 45. PRODUCT WATER FLUX, TEST 78

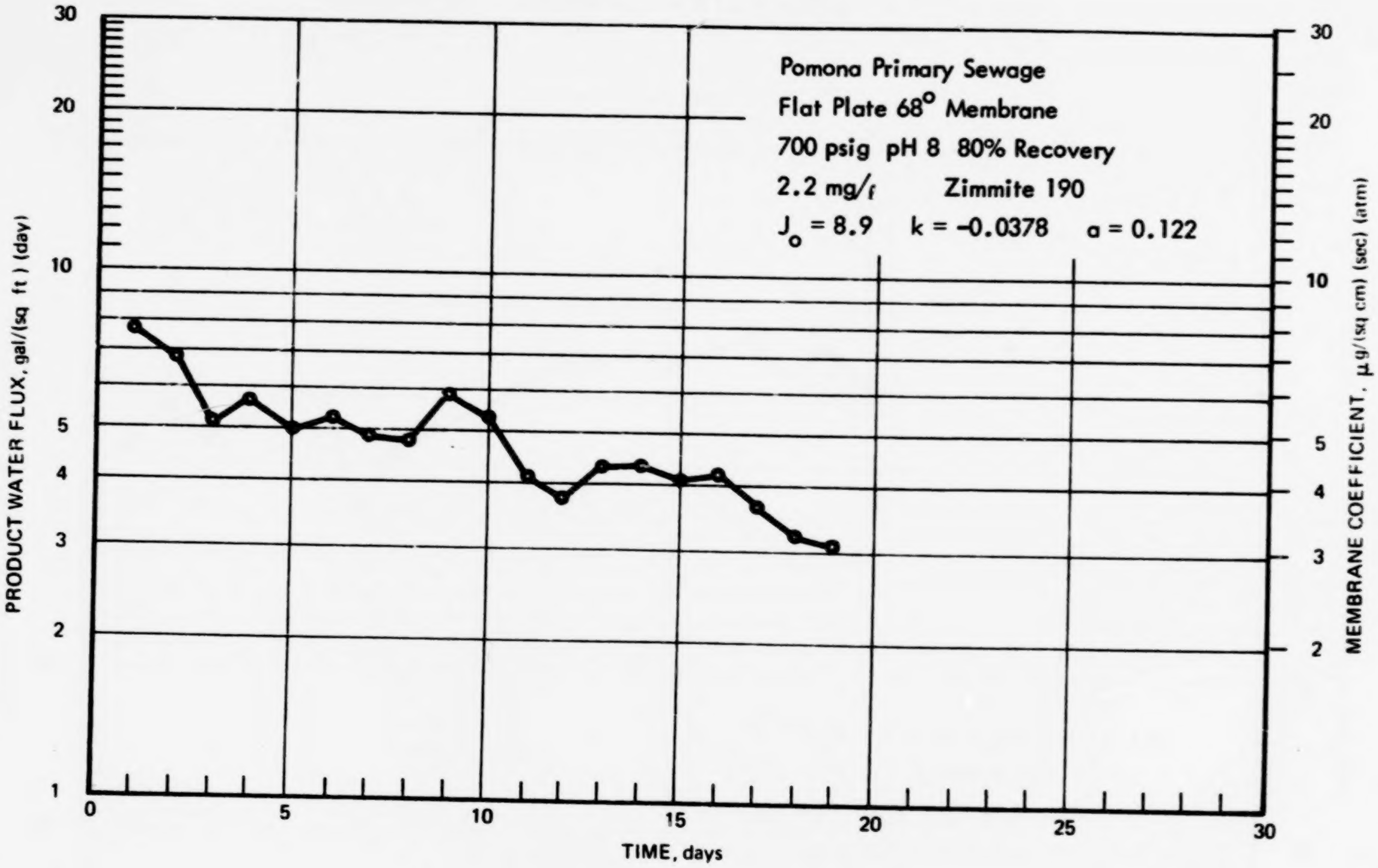

Figure 46. PRODUCT WATER FLUX, TEST 62

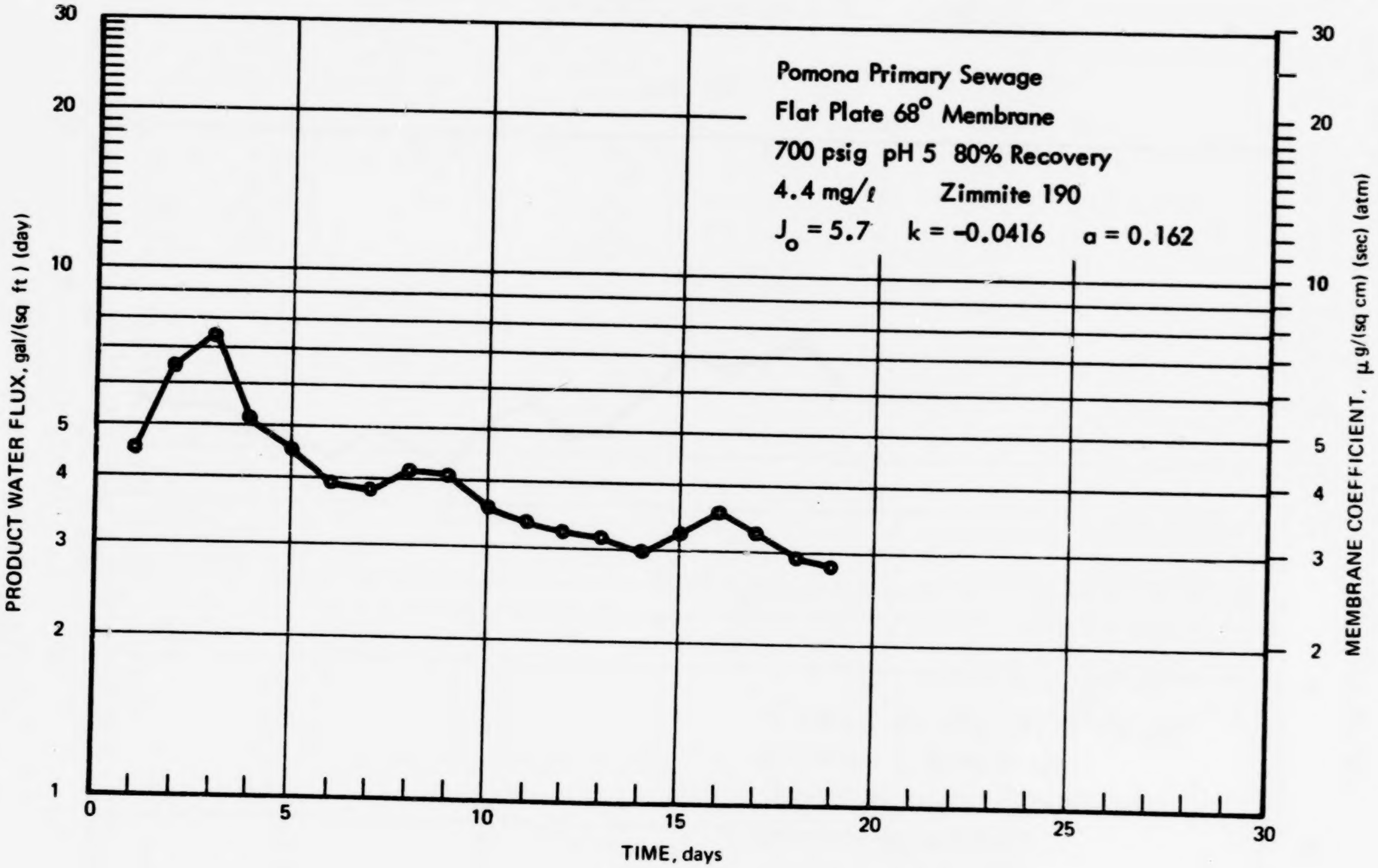

Figure 47. PRODUCT WATER FLUX, TEST 54

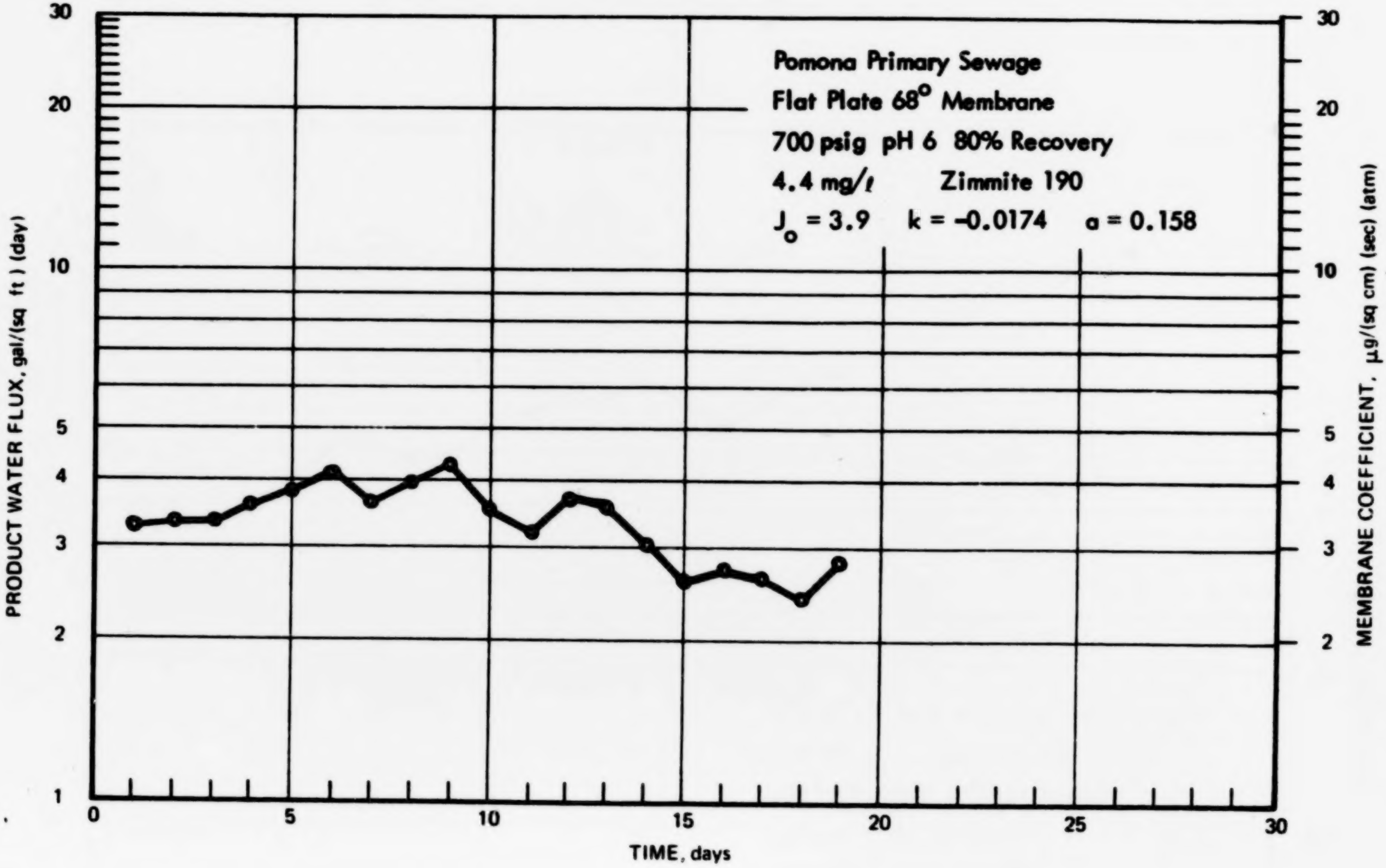

Figure 48. PRODUCT WATER FLUX, TEST 83

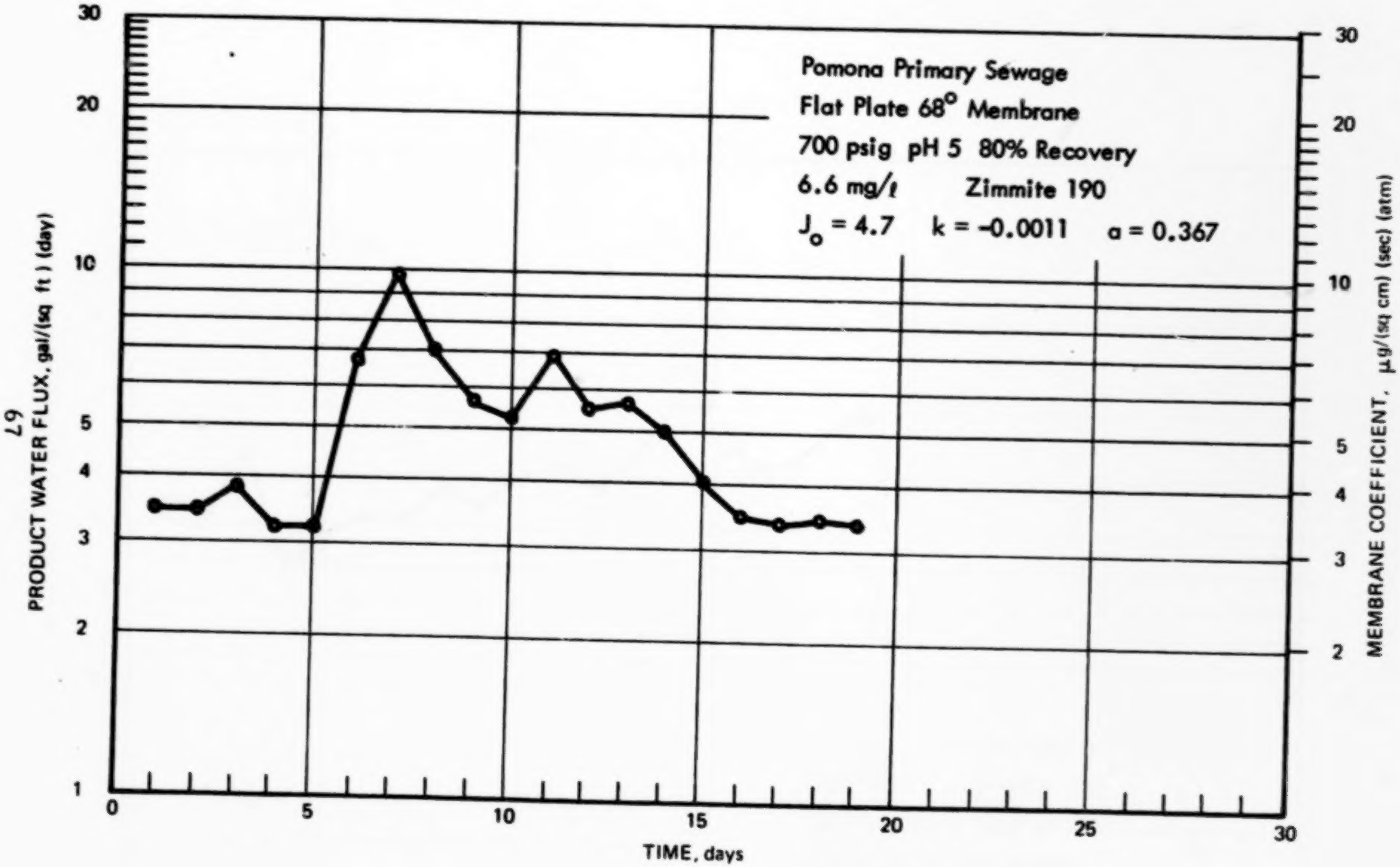

Figure 49. PRODUCT WATER FLUX, TEST 52

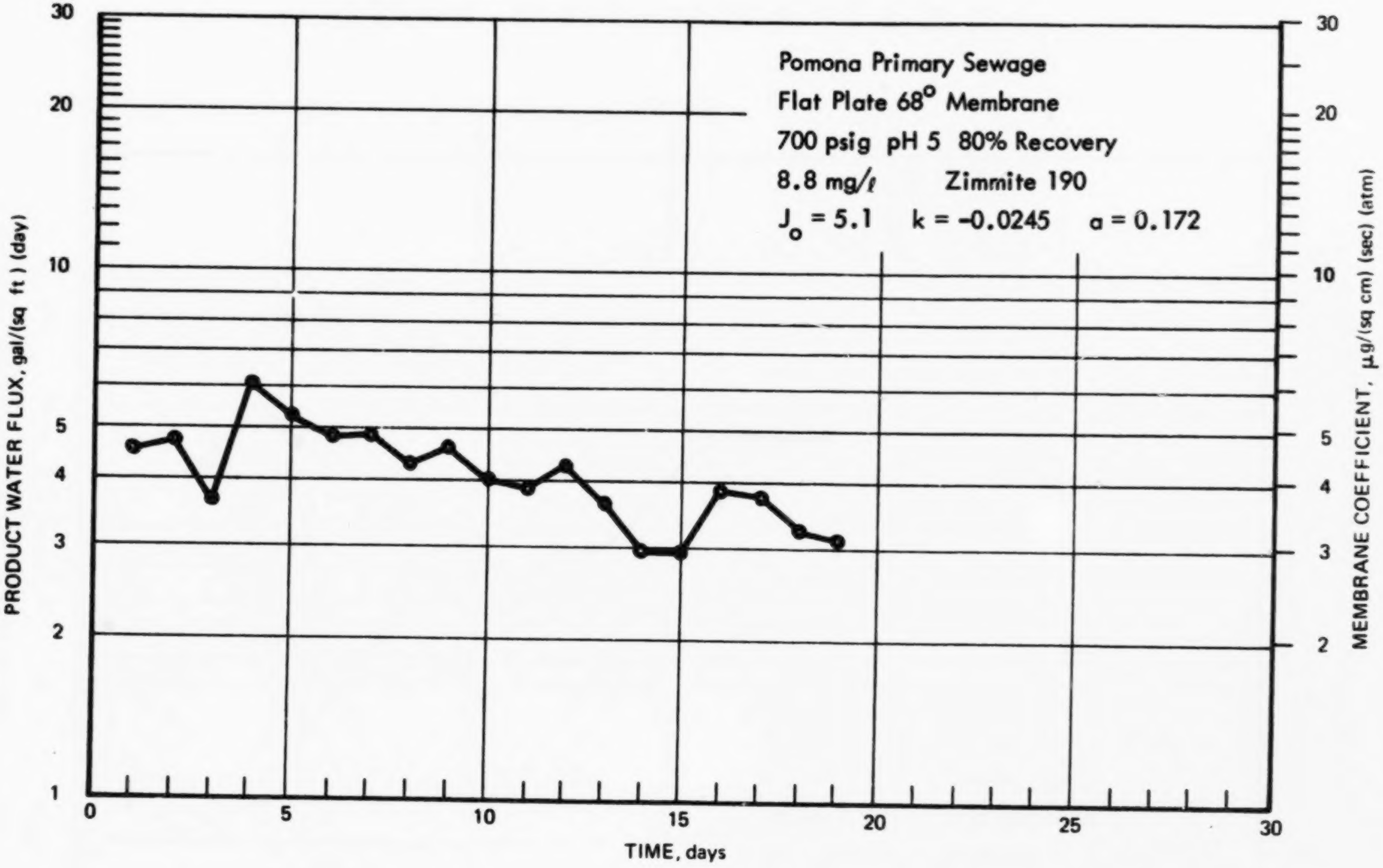

Figure 50. PRODUCT WATER FLUX, TEST 60

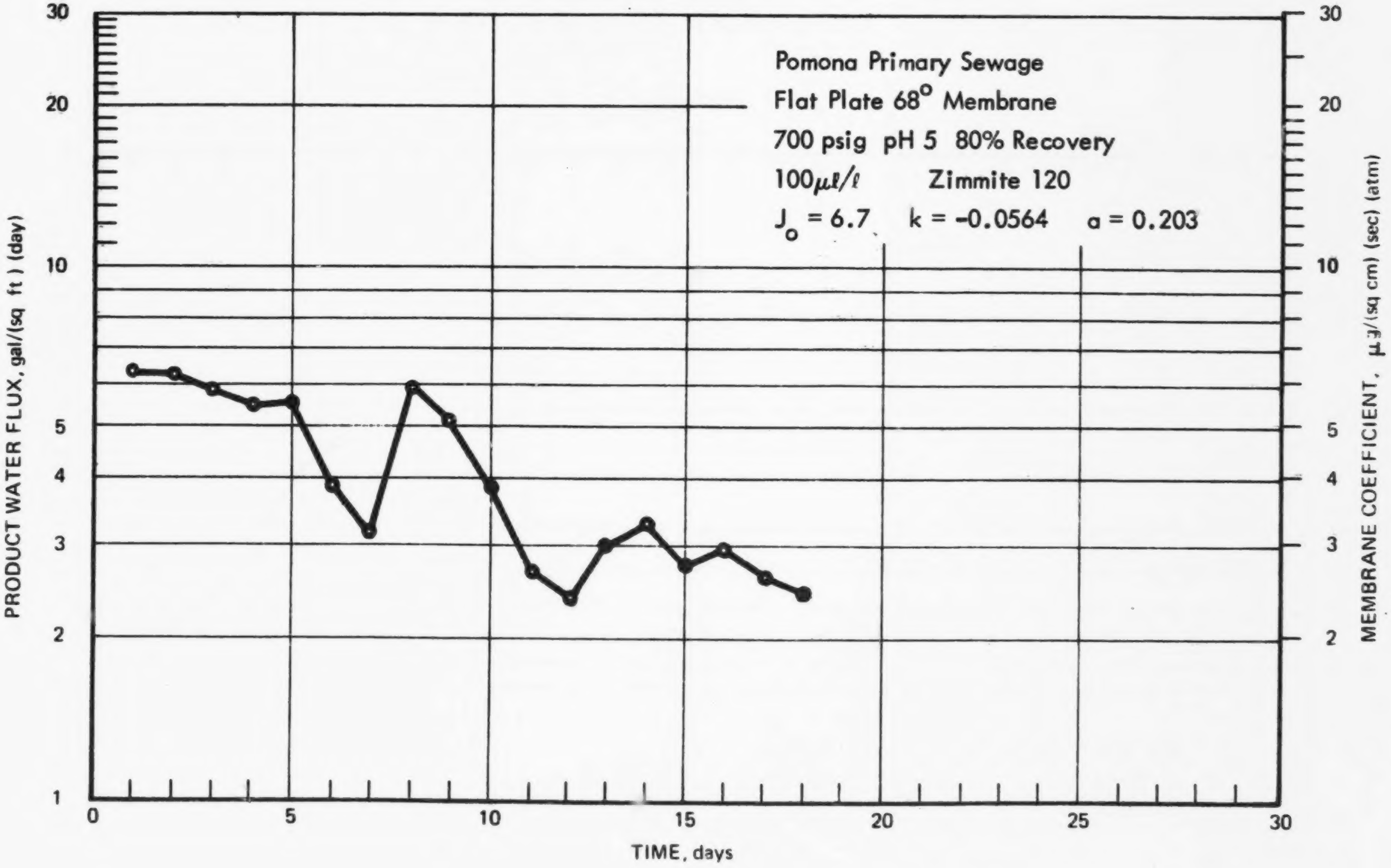

Figure 51. PRODUCT WATER FLUX, TEST 72

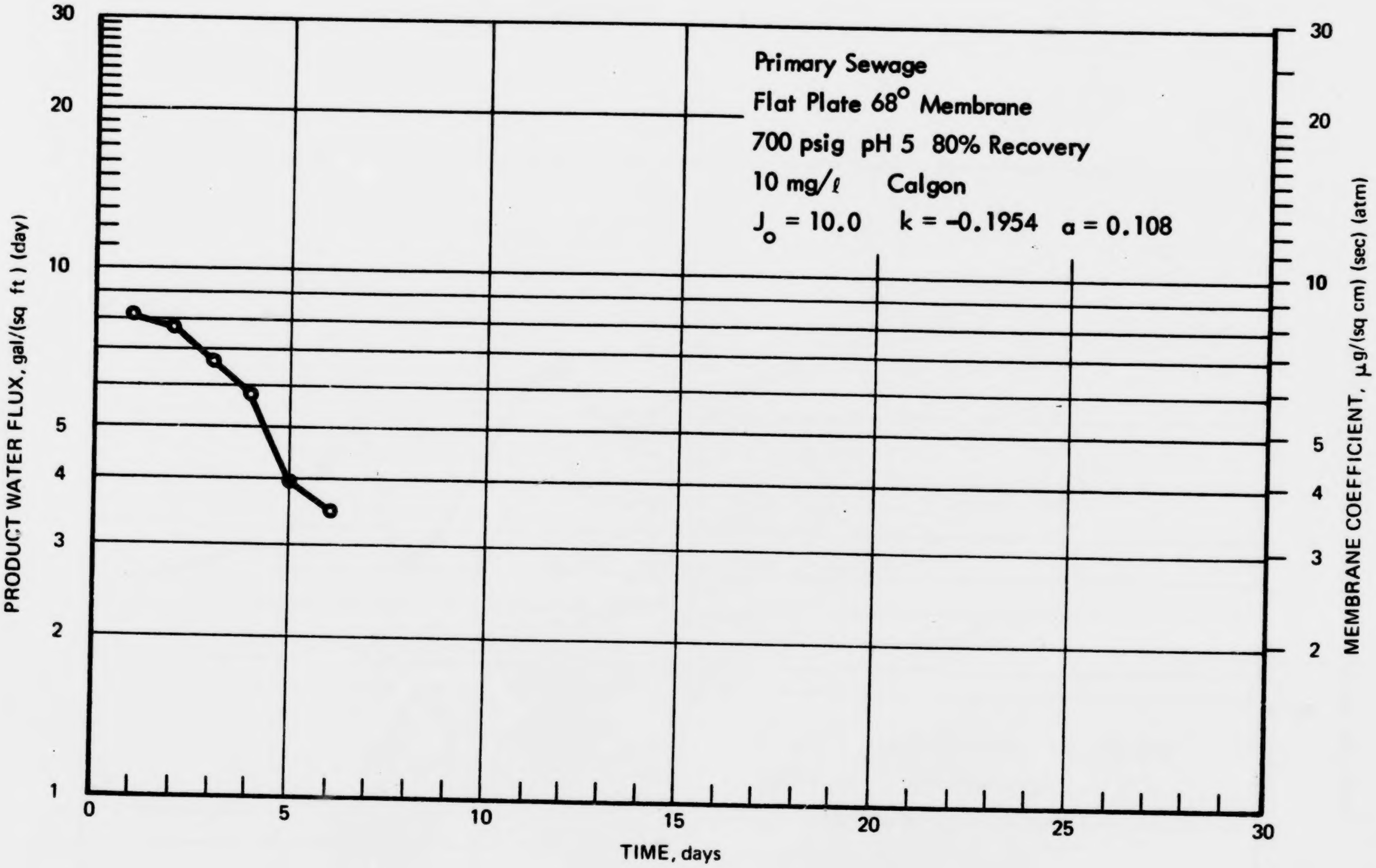

Figure 52. PRODUCT WATER FLUX, TEST 17

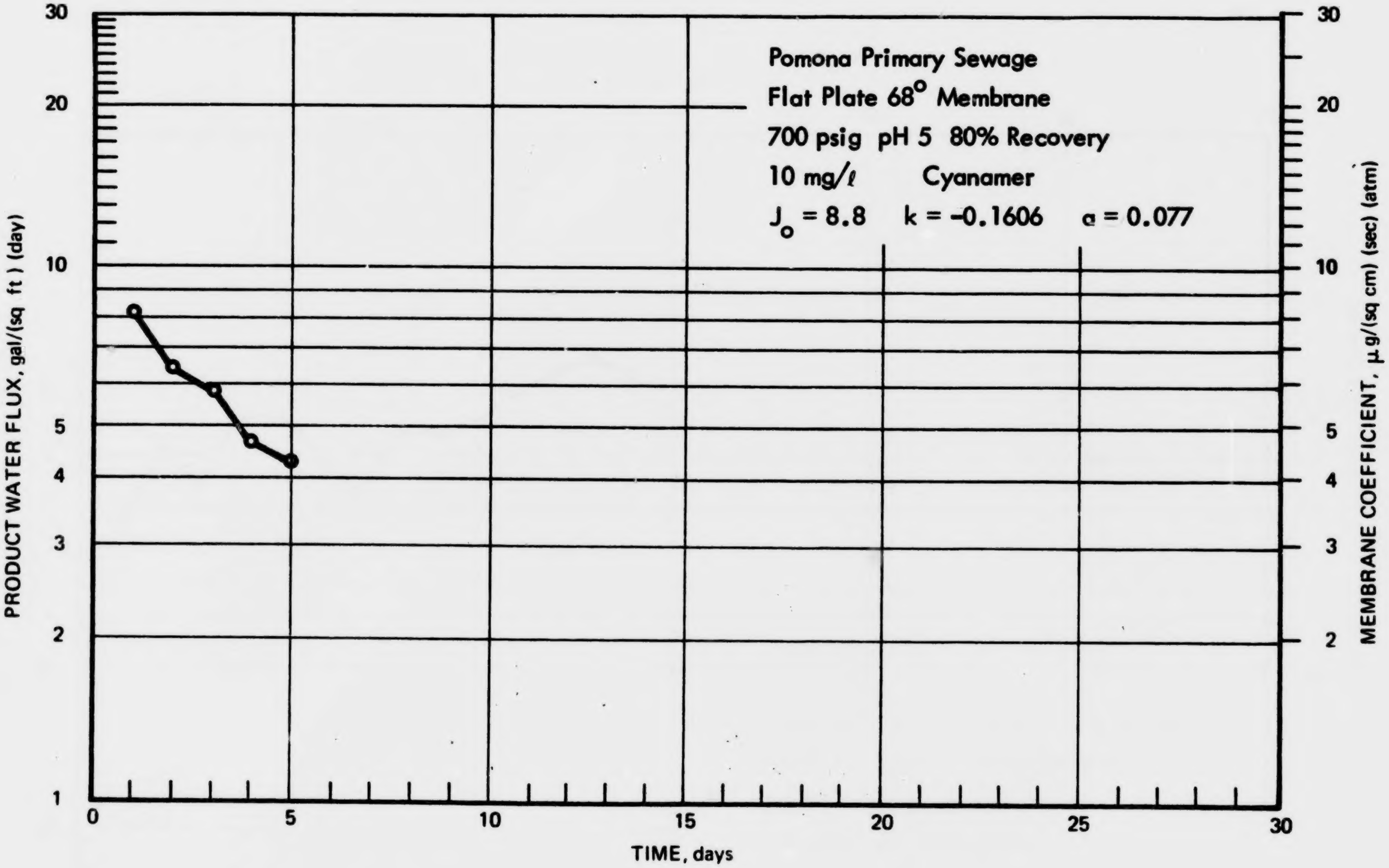

FIGURE 53. PRODUCT WATER FLUX, TEST 15

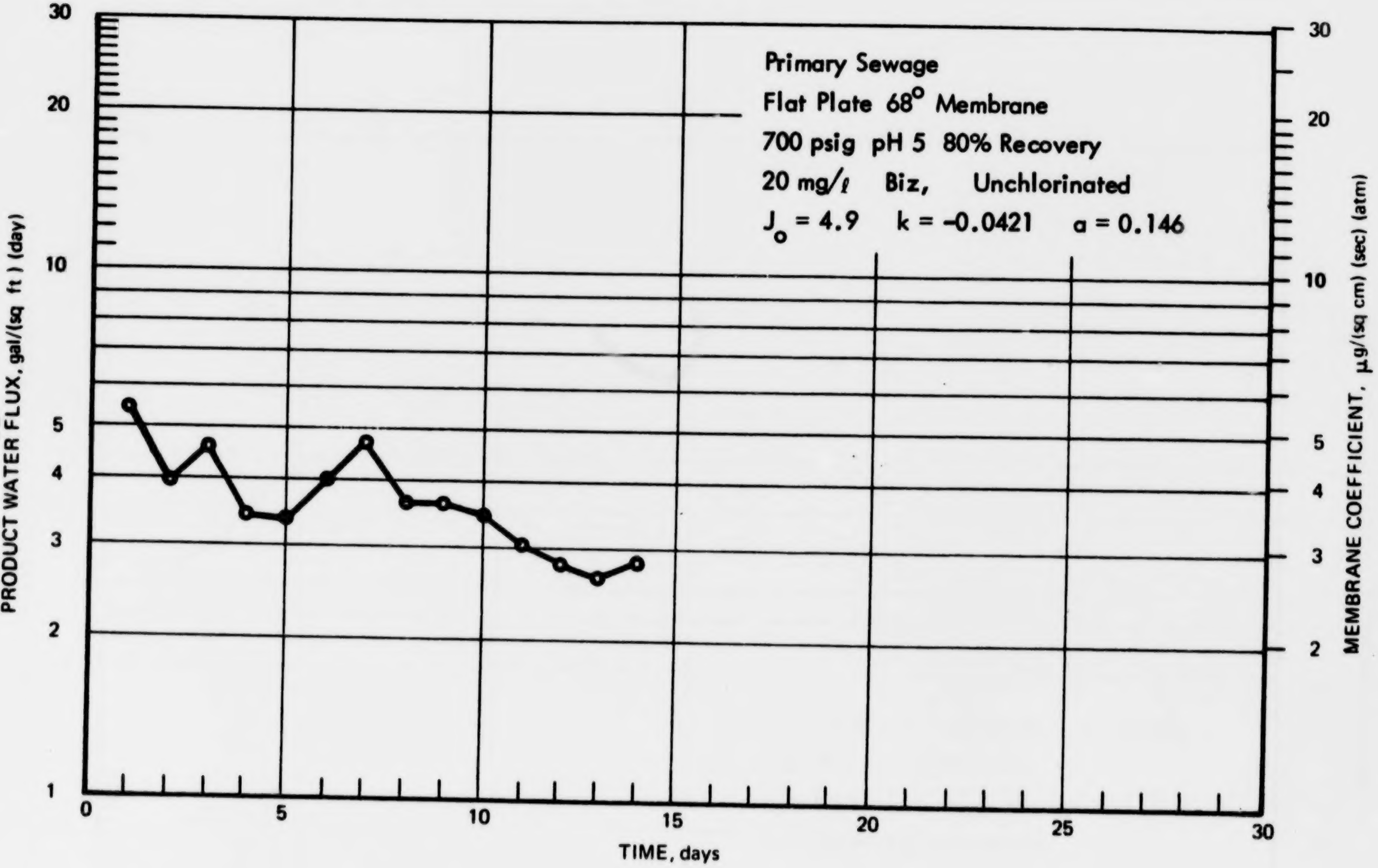

Figure 54. PRODUCT WATER FLUX, TEST 49

Low-pressure treatment of primary sewage is reflected in Figures 55, 56, and 57. These tests were conducted with Zimmite 190 at two dosages and pH values of 5 and 6 in an attempt to produce a very low flux decline.

Raw Sewage

The treatment of homogenized raw sewage was attempted in the flat-plate test cells with the high pressure membranes. Figures 58, 59, 60, and 61 reveal the product water fluxes achieved while processing the raw sewage. In most cases, the membrane material became perforated and leaked due to cuts and scratches on the membrane surface resulting most likely from hard, suspended particles contained in the raw sewage.

Digester Sewage

Figures 62, 63, 64, and 65 show that treatment of the material from mixed anaerobic sludge digestion tanks is possible with reverse osmosis, but that severe fouling of the membrane surface will occur and the product water flux will be very poor. The test runs were quickly terminated as being impractical, even with the addition of the fixed dosages of Zimmite 190, Calgon, and Cyanamer.

Tubular Membranes

The following presentation includes all the tests conducted with tubular membranes under various operating conditions and is presented according to type or quality of feed water.

Carbon-treated Secondary Sewage

The product water fluxes obtained while processing carbon-treated secondary effluent with tubular membranes are probably not representative of those obtainable, due to several factors. Figures 66 and 67 show results that were probably influenced by residual deposits of waste in the testing equipment from previous sewage feeds. The membrane surfaces were coated with a pale greenish scum that was not typical of earlier tests conducted on carbon-treated sewage. Moreover, Test 51 (Figure 66) was conducted with a plunger pump which is believed to have contributed to the system fouling by shredding of its packing. Also these tests were performed on sewage feeds collected from the reduced capacity, partially exhausted activated-carbon treatment columns.

Secondary Sewage

There were two control tests for secondary sewage with the tubular membrane. Test 44, shown in Figure 68, was contaminated by shredded pump packing and was rerun as Test 57, presented in Figure 69. The pretreatment of secondary sewage by alum clarification produced relatively stable product water fluxes as may be seen in Figures 70, 71, and 72. Test 37 (Figure 70) utilized the plunger pump but with a different packing material that extruded excessively under pressure. Test 70

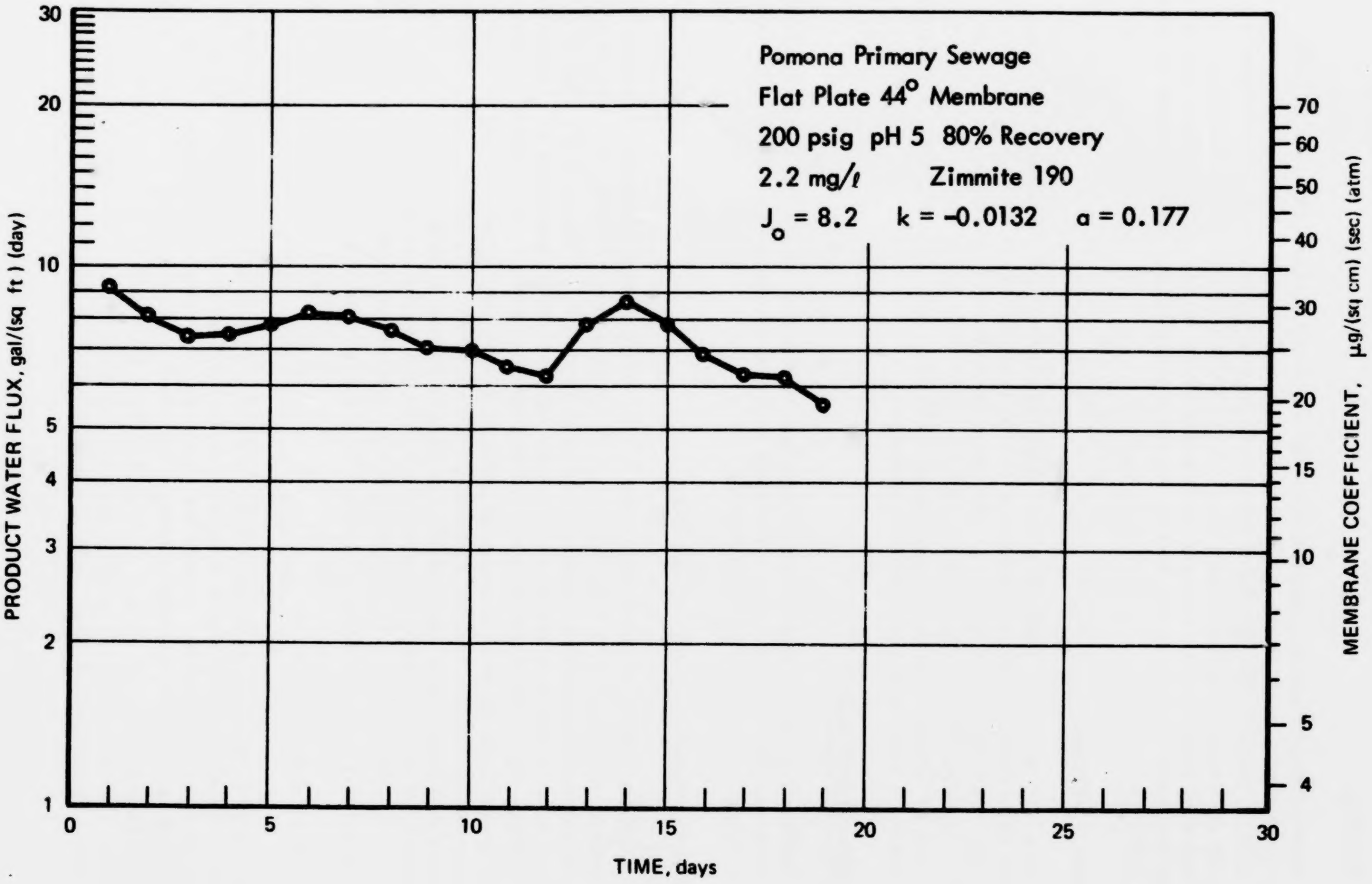

Figure 55. PRODUCT WATER FLUX, TEST 65

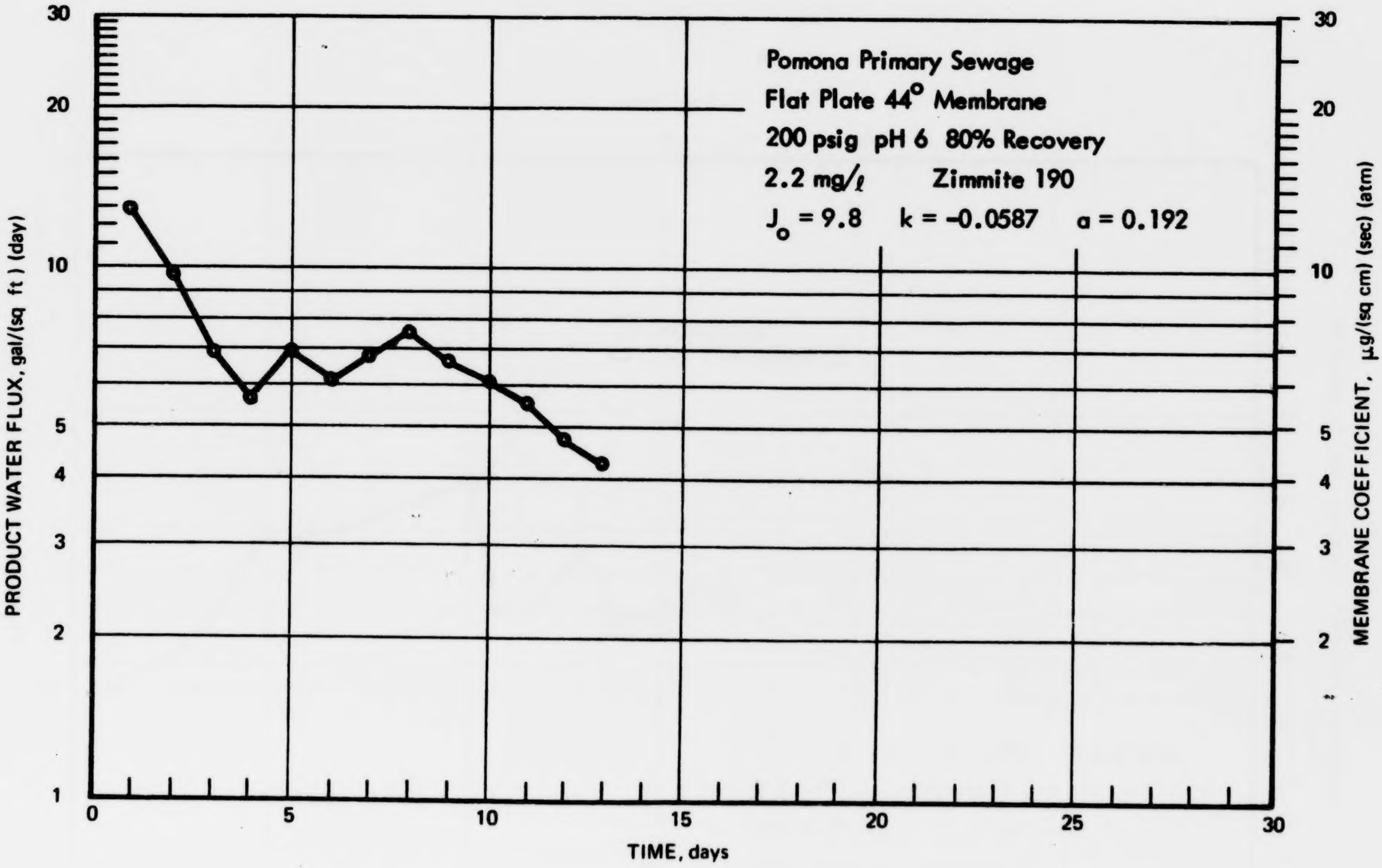

Figure 56. PRODUCT WATER FLUX, TEST 80

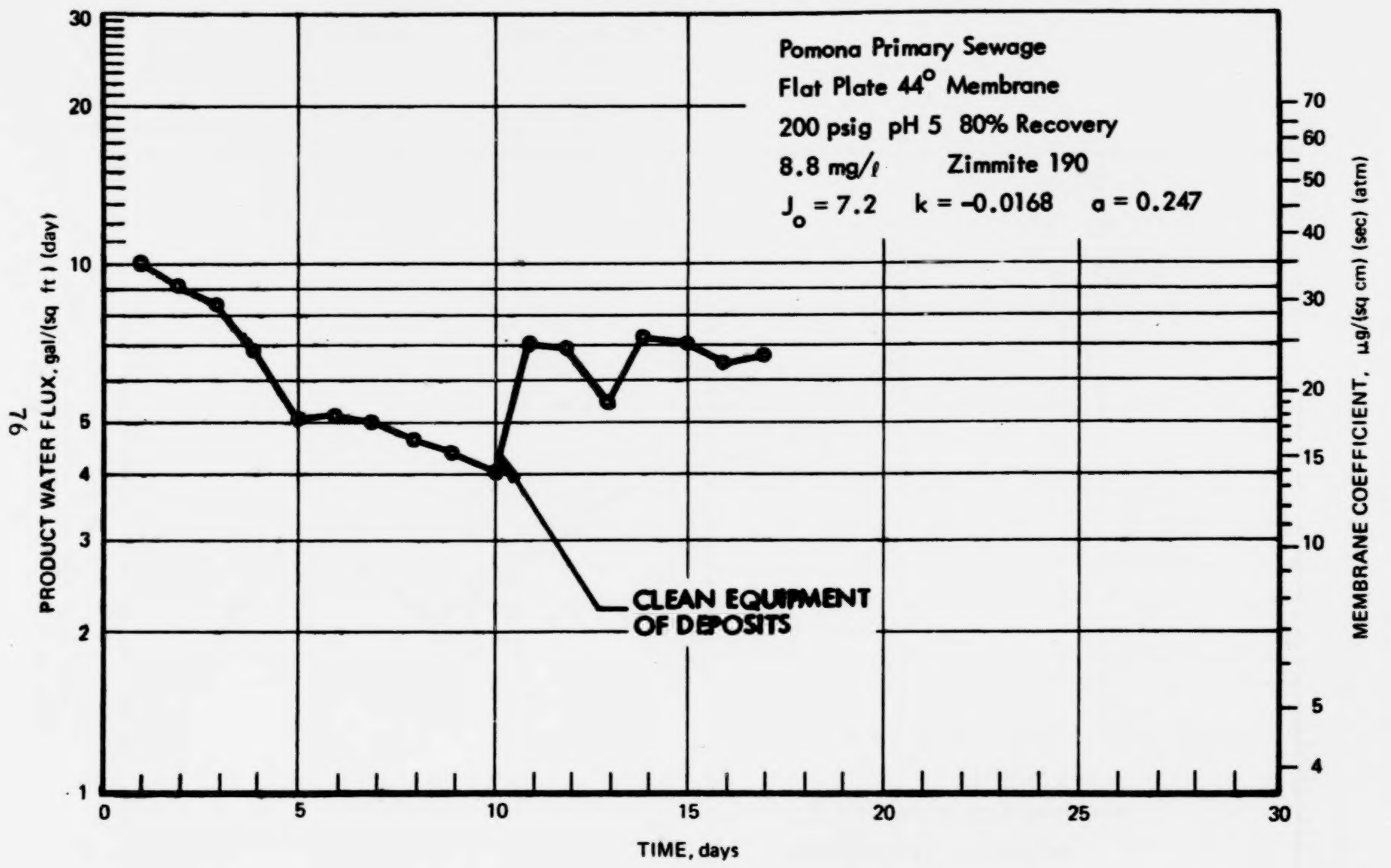

Figure 57. PRODUCT WATER FLUX, TEST 68

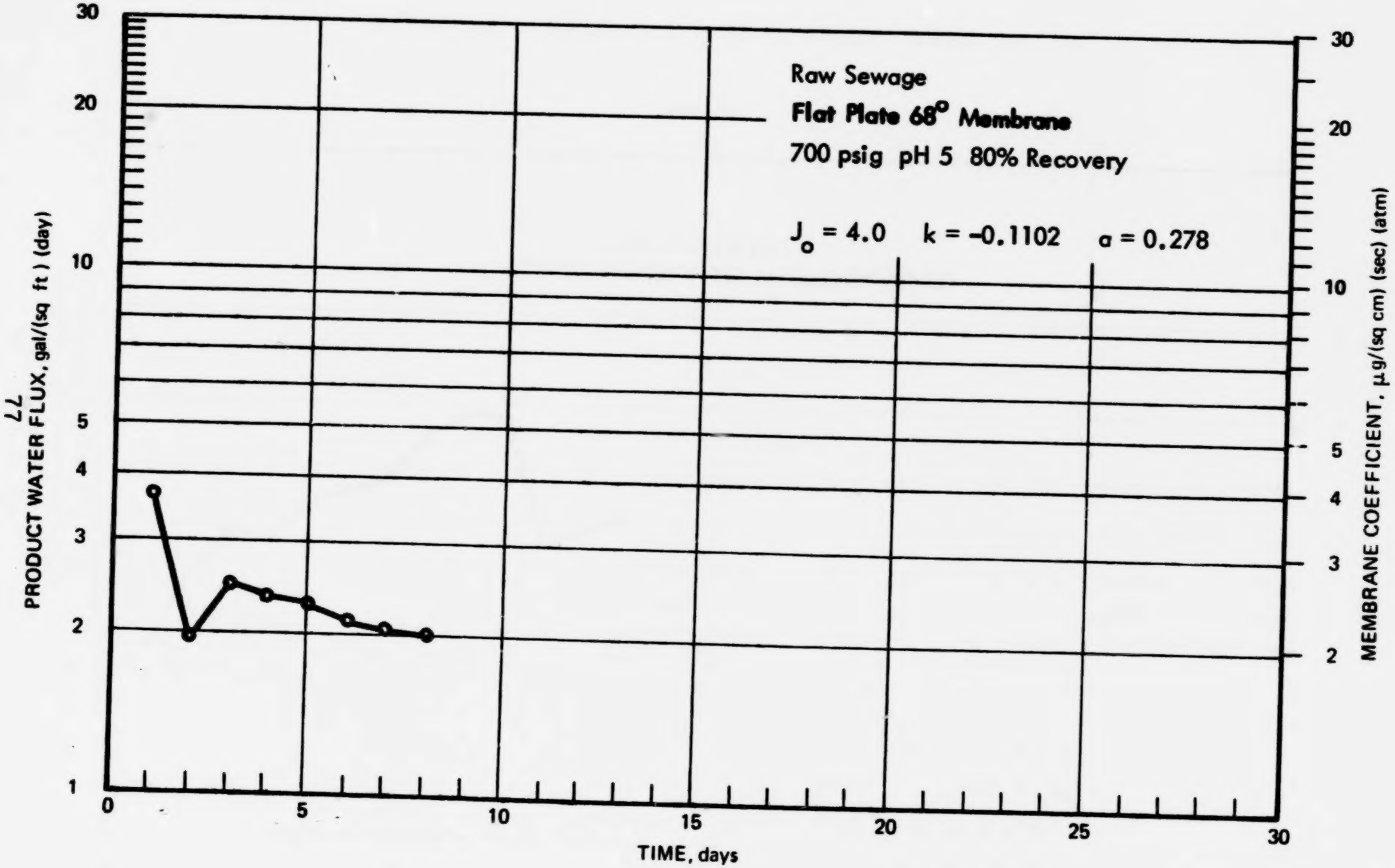

Figure 58. PRODUCT WATER FLUX, TEST 18

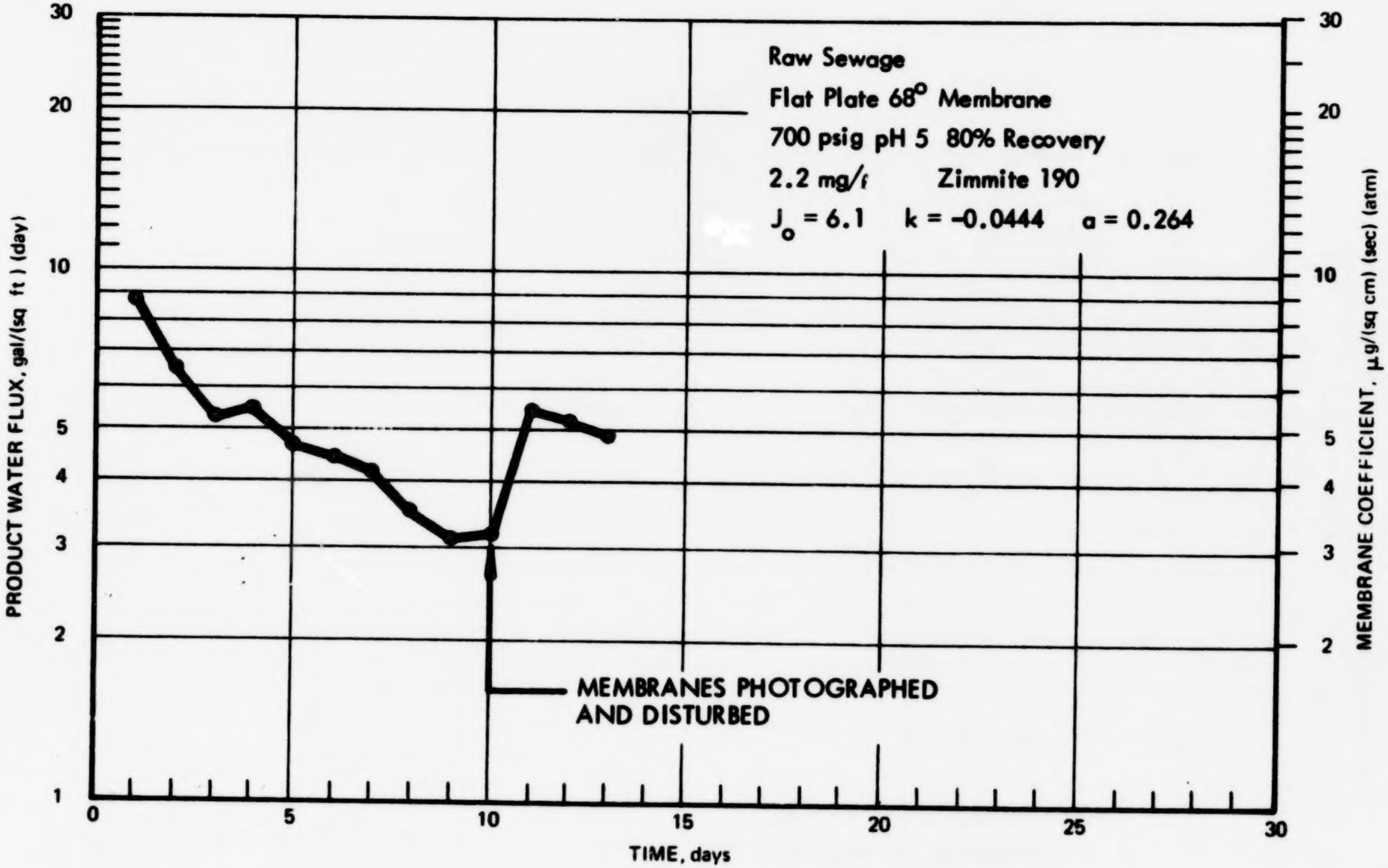

Figure 59. PRODUCT WATER FLUX, TEST 20

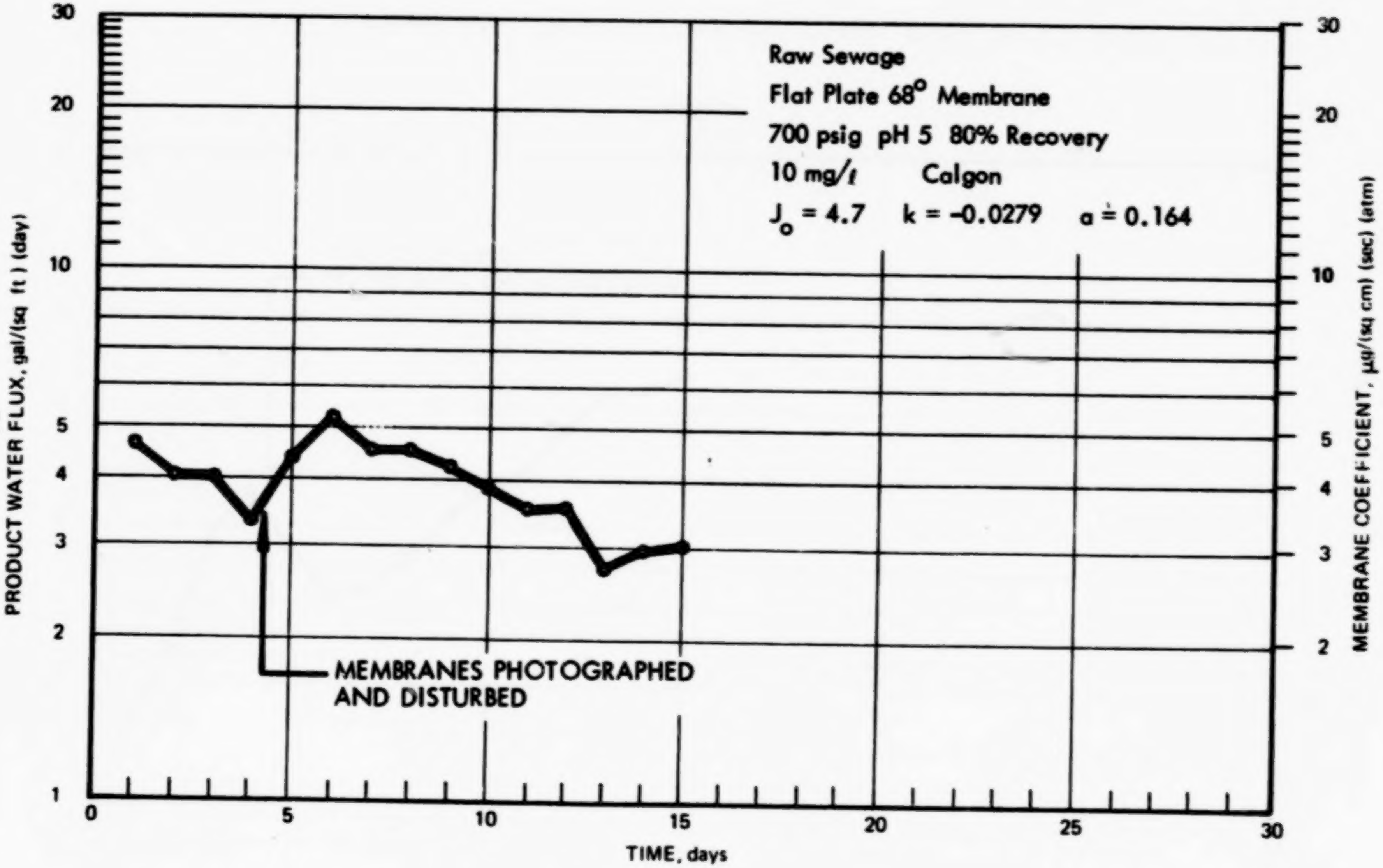

Figure 60. PRODUCT WATER FLUX, TEST 24

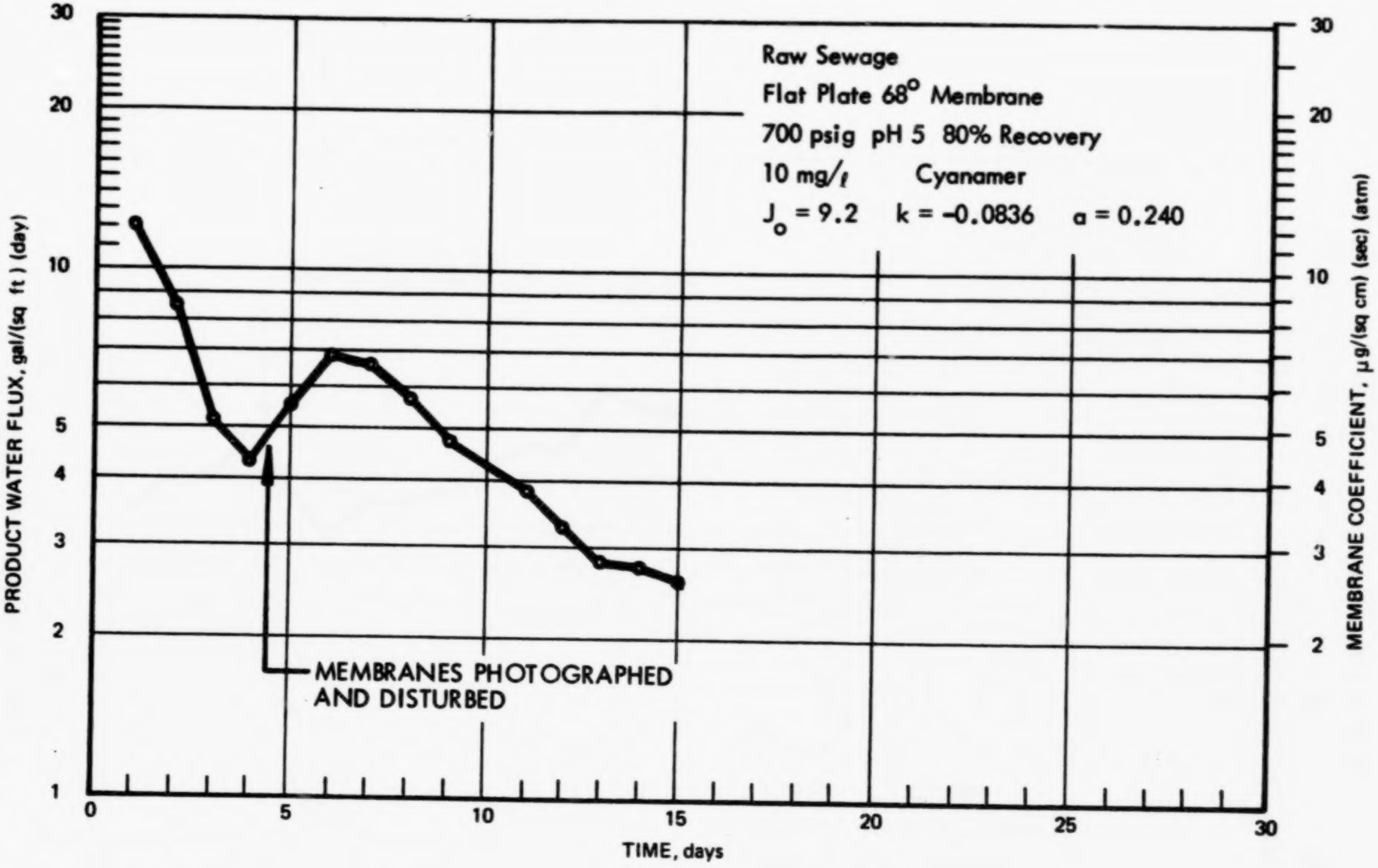

Figure 61. PRODUCT WATER FLUX, TEST 25

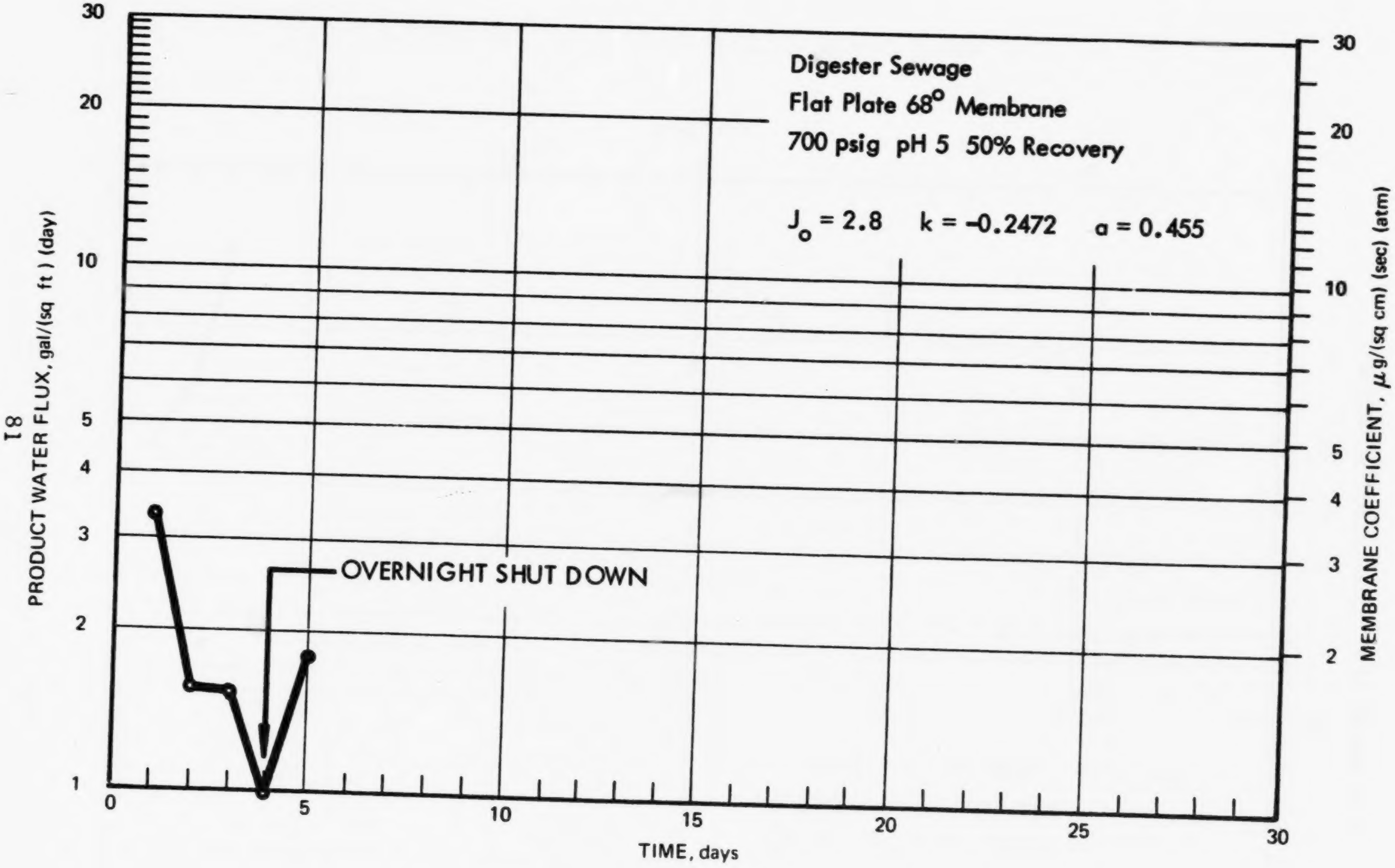

Figure 62. PRODUCT WATER FLUX, TEST 23

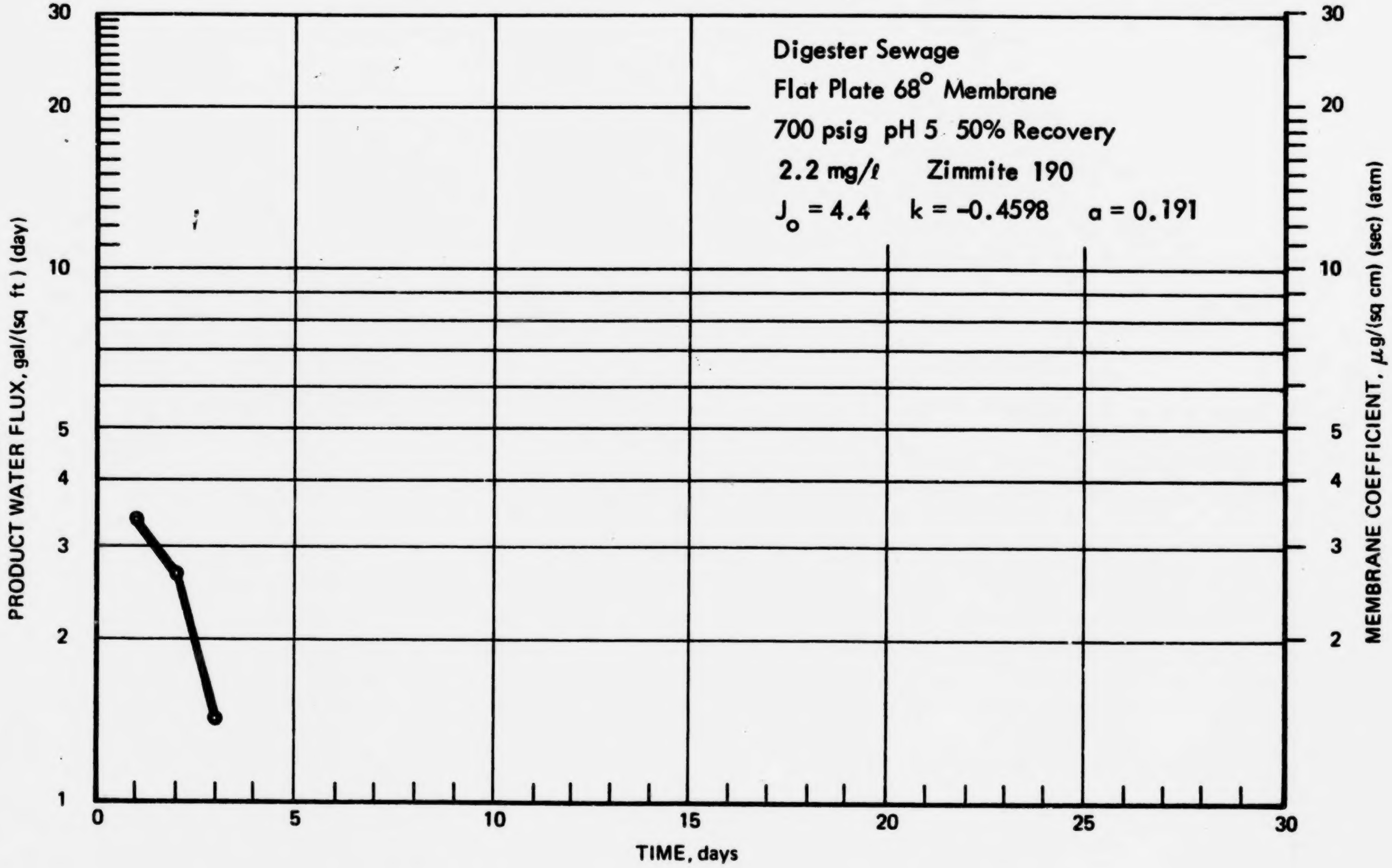

Figure 63. PRODUCT WATER FLUX, TEST 29

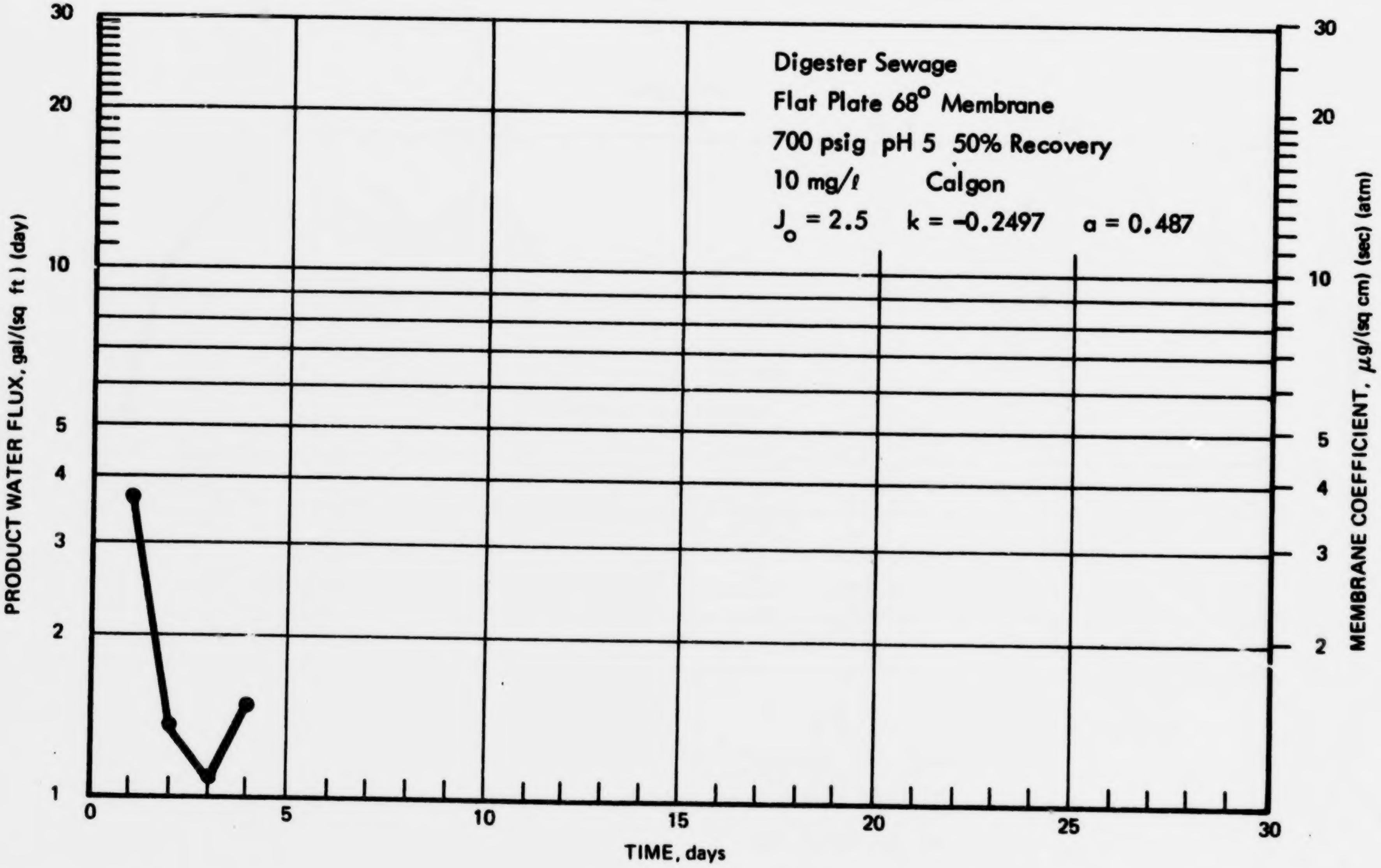

Figure 64. PRODUCT WATER FLUX, TEST 27

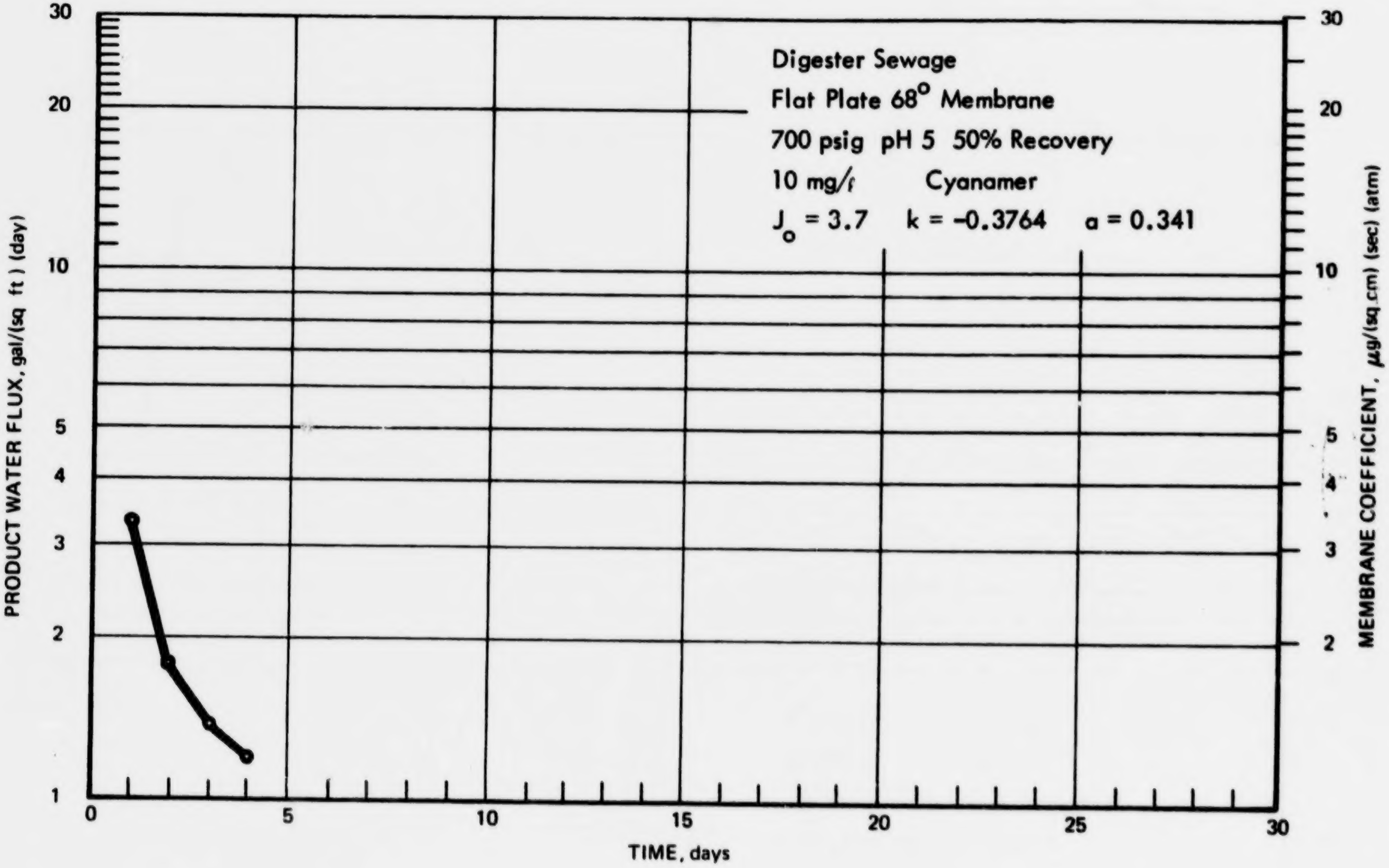

Figure 65. PRODUCT WATER FLUX, TEST 28

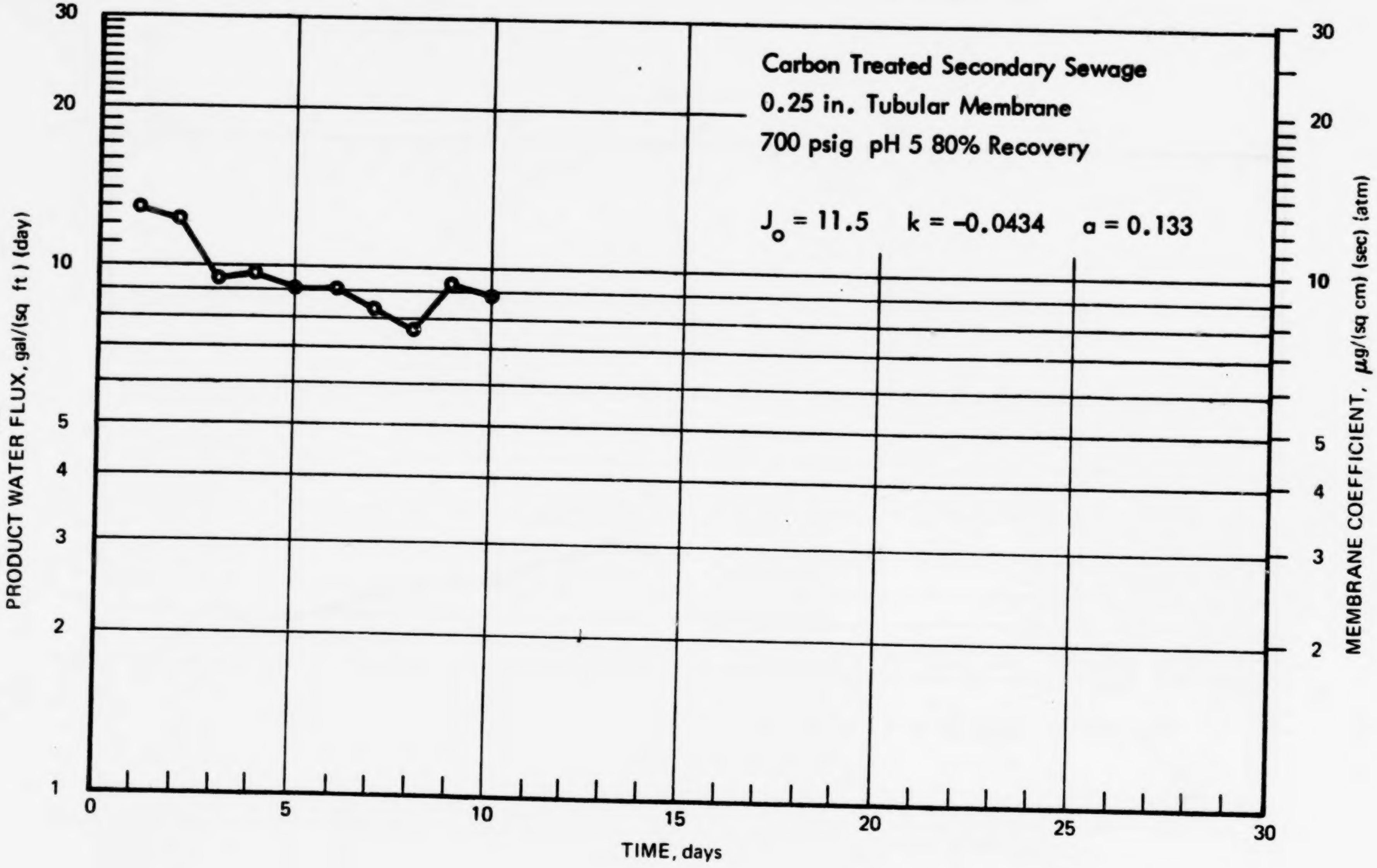

Figure 66. PRODUCT WATER FLUX, TEST 51

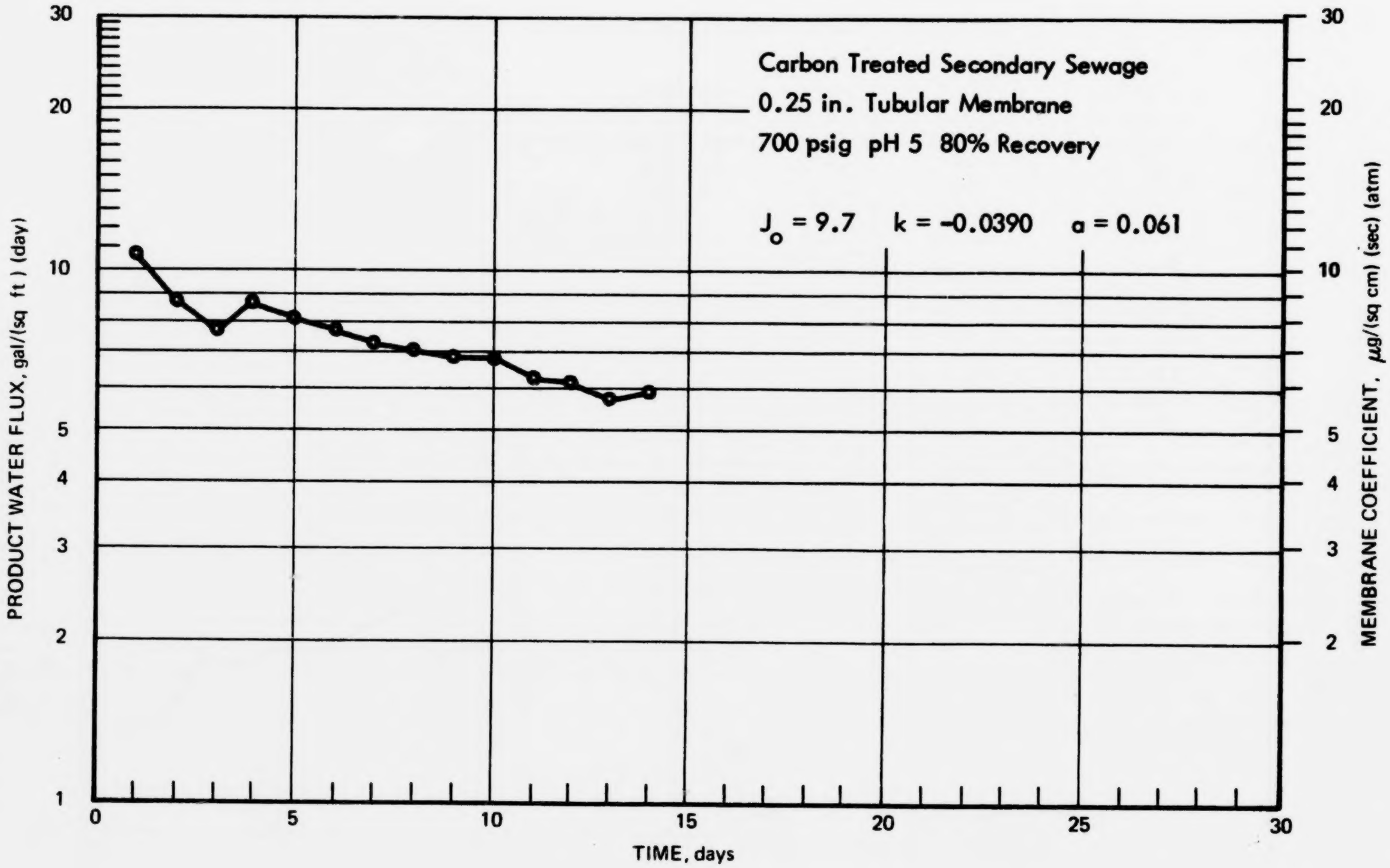

Figure 67. PRODUCT WATER FLUX, TEST 56

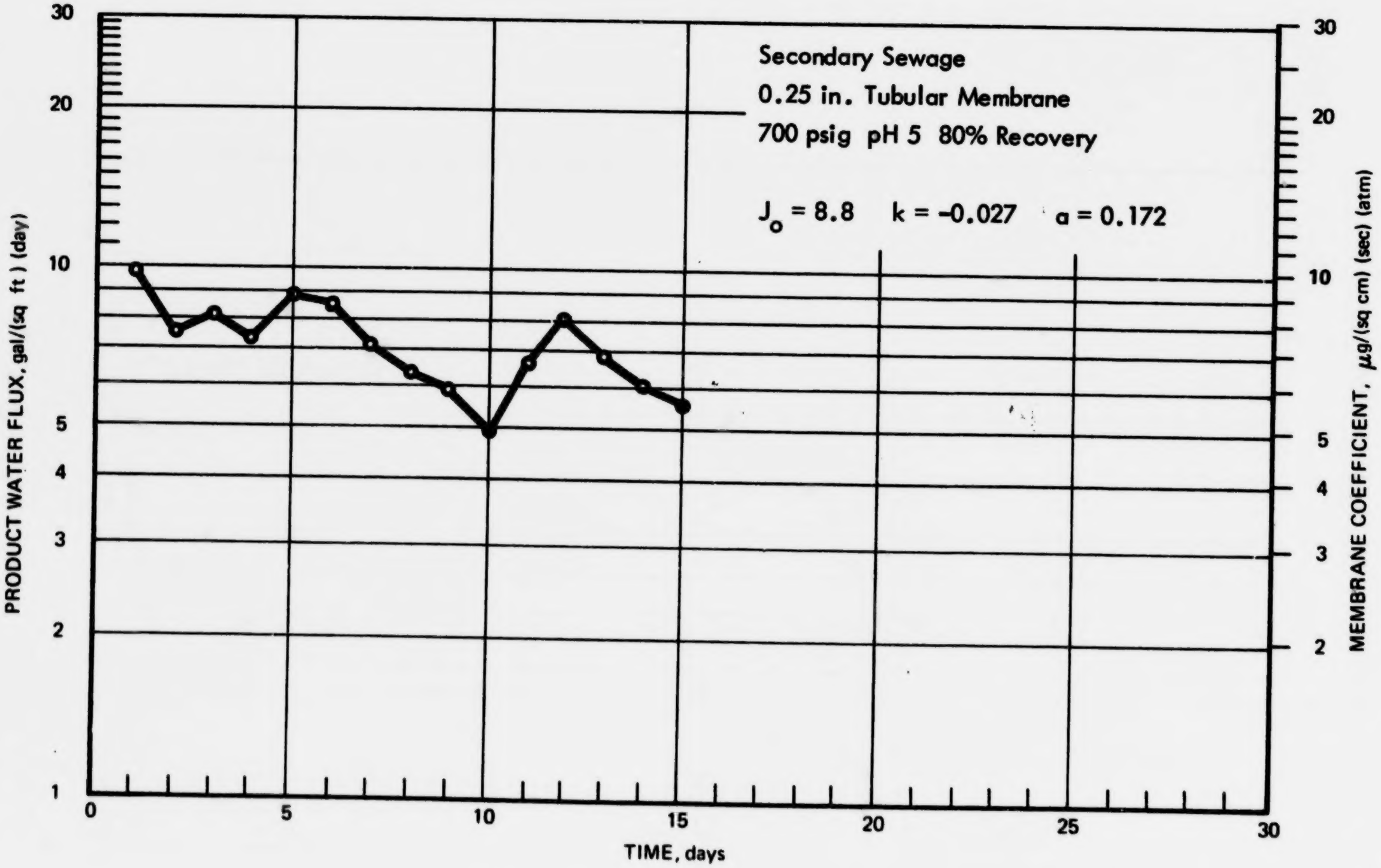

Figure 68. PRODUCT WATER FLUX, TEST 44

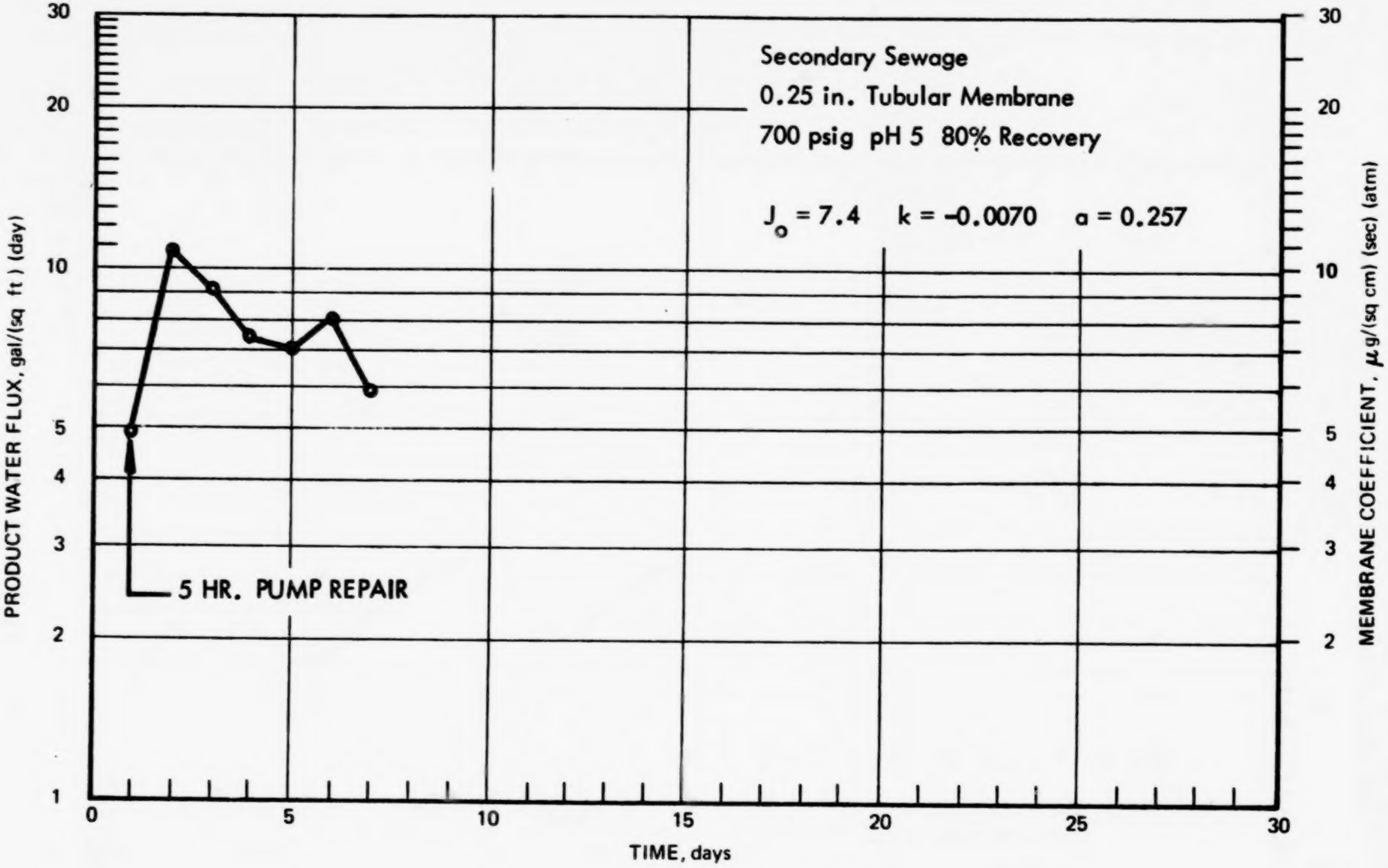

Figure 69. PRODUCT WATER FLUX, TEST 57

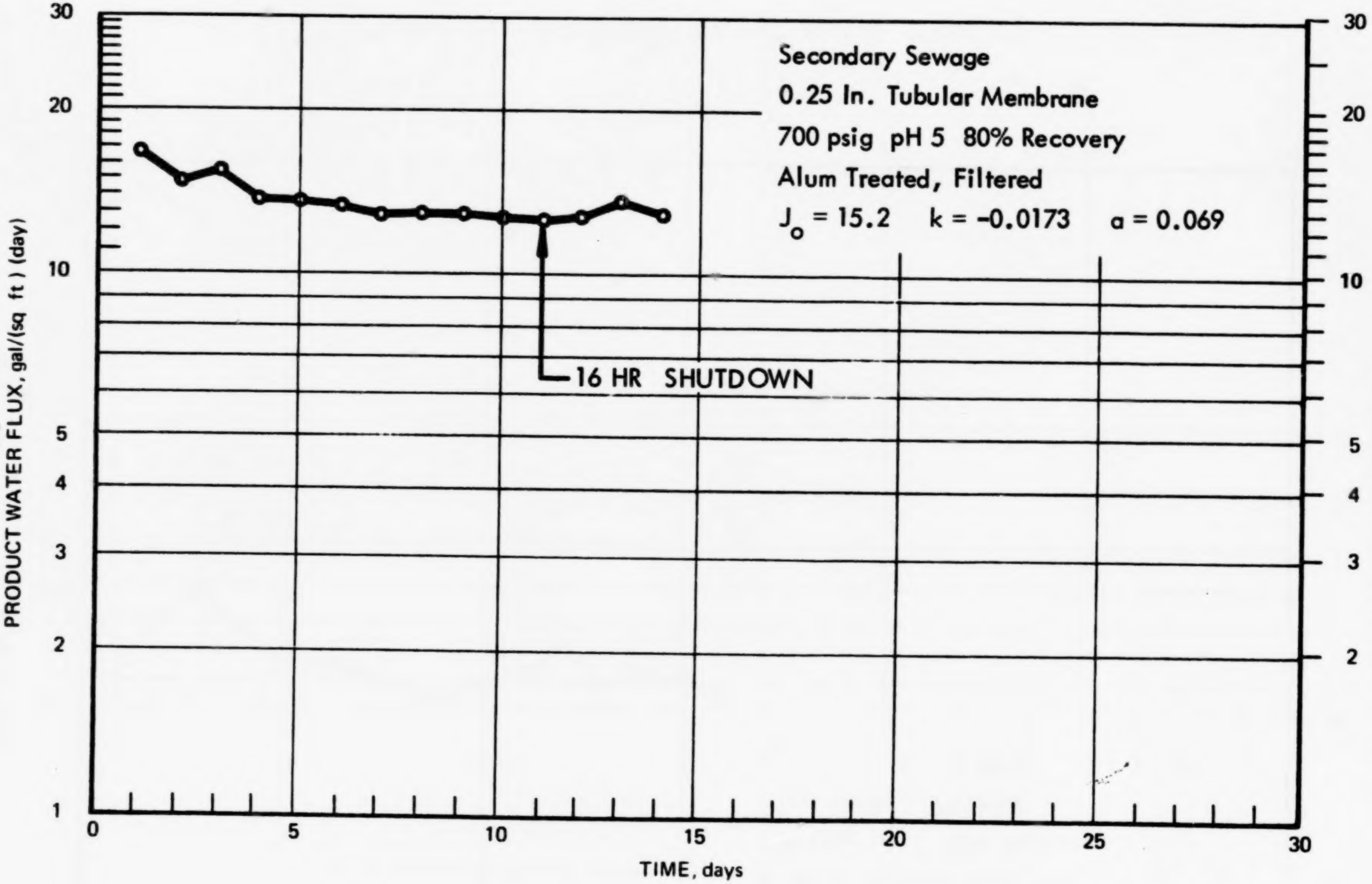

FIGURE 70. PRODUCT WATER FLUX, TEST 37

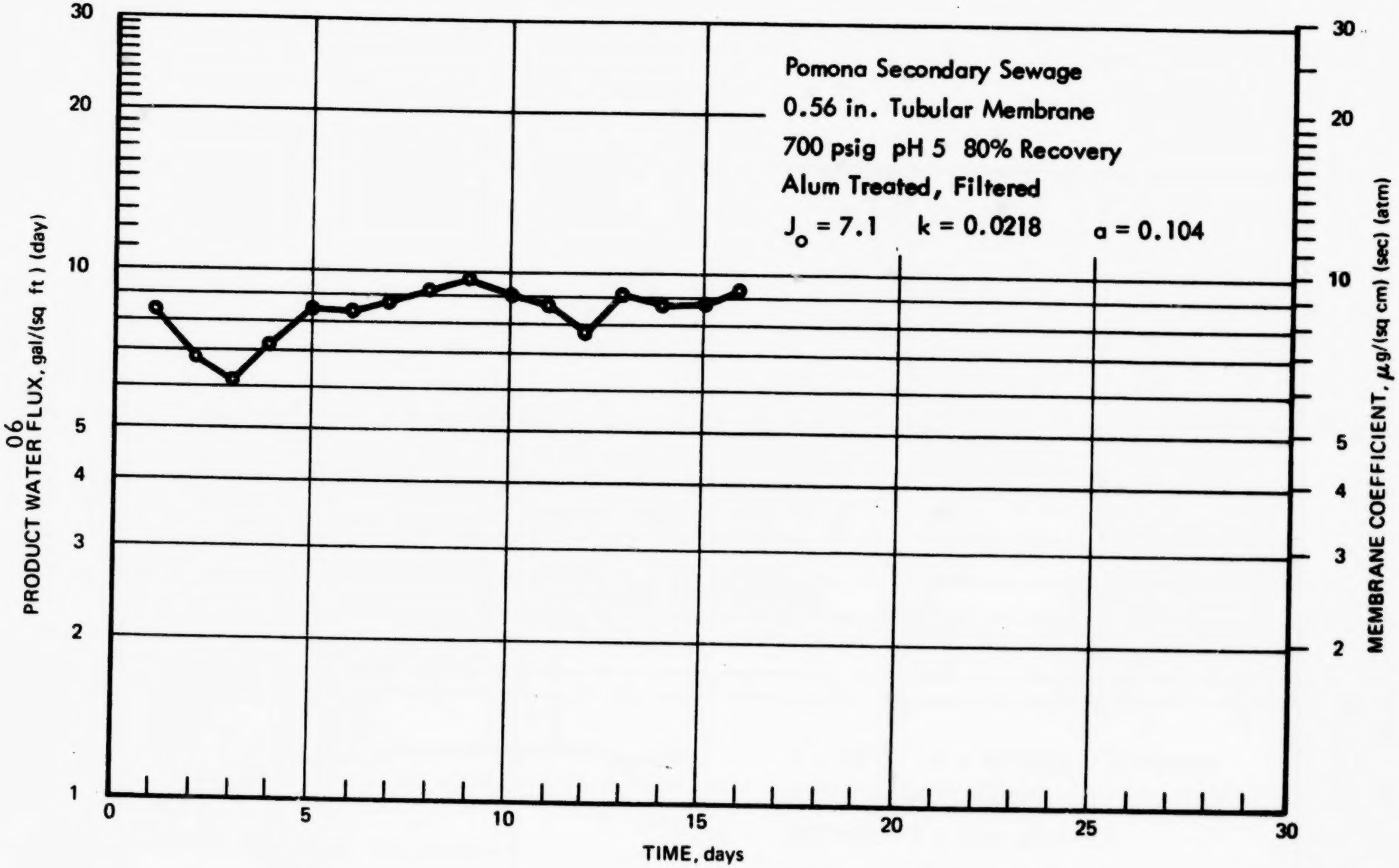

Figure 71. PRODUCT WATER FLUX, TEST 75

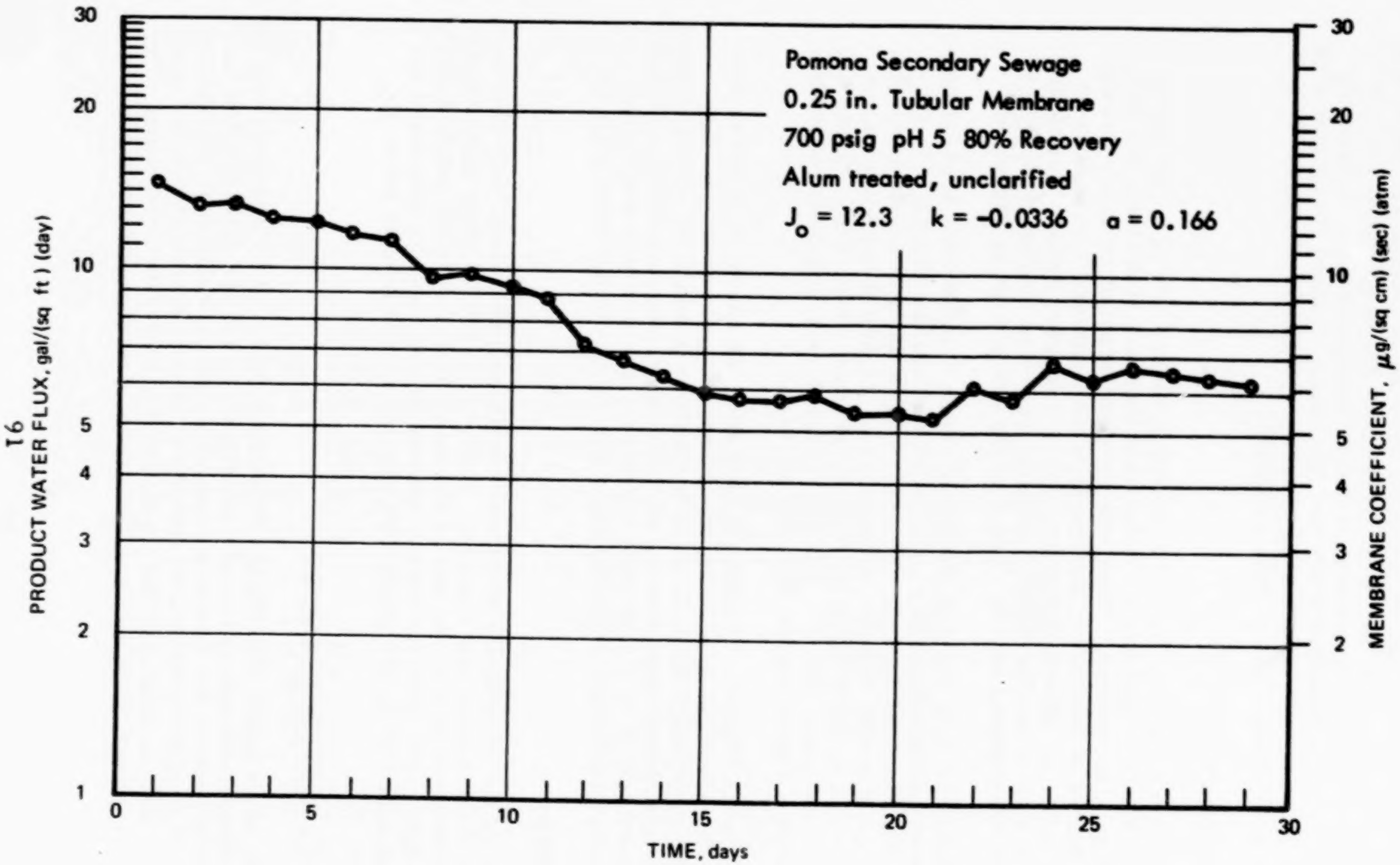

Figure 72. PRODUCT WATER FLUX, TEST 70

(Figure 72) produced a surprisingly stable flux with alum-treated, settled, and then thoroughly remixed secondary sewage.

The effects of the addition of Zimmite 190 and of Calgon are presented in Figures 73, 74, and 75. Test 58 (Figure 74) is a retrial of Test 45 (Figure 73) which had experienced the packing problem. Relatively high stable fluxes resulted from the combining of alum treatment with Zimmite 190 and with Cyanamer. Figures 76 and 77 illustrate two of the most promising tests of this program.

Primary Sewage

Figure 78 presents the control test with primary sewage. In sharp contrast, Figure 79 shows a 77-day test that had stabilized at a flux of 4 to 5 gal/(sq ft)(day). This test on alum-treated primary sewage was conducted at 80-, 90-, and 95-percent recovery levels with no apparent adverse effects from the higher recovery ratio. Just prior to termination of the program a similar test was started with Dow C-31 as the flocculating agent. The results are shown in Figure 80.

The effectiveness of varying the pH between 5 and 6 with several concentrations of Zimmite 190 is recorded in Figures 81, 82, 83, 84, 85, 86, 87, and 88. In Test 55 (Figure 82) a daily 2.5-min tap water flush of the 0.25-in. tubular membrane at 12,500 Reynolds number was instituted in an attempt to restore product water flux. Tests 81, 86, and 91 (Figures 86, 87, and 88, respectively) experienced rather stable fluxes with Zimmite 190 at a pH of 6.

The tests with Calgon, Cyanamer, and Biz, as shown in Figures 89, 90, and 91, resulted in at least one interesting observation. Biz, which had previously been used as a continuous additive, was now used for a 15-min membrane soaking at 2,000 mg/l concentration. Following a 15-min flush at 1 gpm with tap water, the product water flux through the membrane experienced a strong but temporary recovery.

Raw Sewage

Because of the previously observed membrane abrasion, only two tests were conducted with raw sewage. Figures 92 and 93 show the results of no pretreatment and the use of Zimmite 190 to control product water flux decline. The heavier solids content of raw sewage may have inactivated most of the Zimmite 190 causing no net benefit from the additive.

PRODUCT WATER QUALITY

Average wastewater constituent rejections obtained in this program for each of the membrane types are presented in Tables 3, 4, 5, and 6, which also contain the average product water pollutant concentrations. The 68° flat-plate membranes and the 0.25-in. diameter tubular membranes exhibited very similar wastewater constituent rejections. The 44° flat-plate membranes demonstrated poorer rejections at the benefit

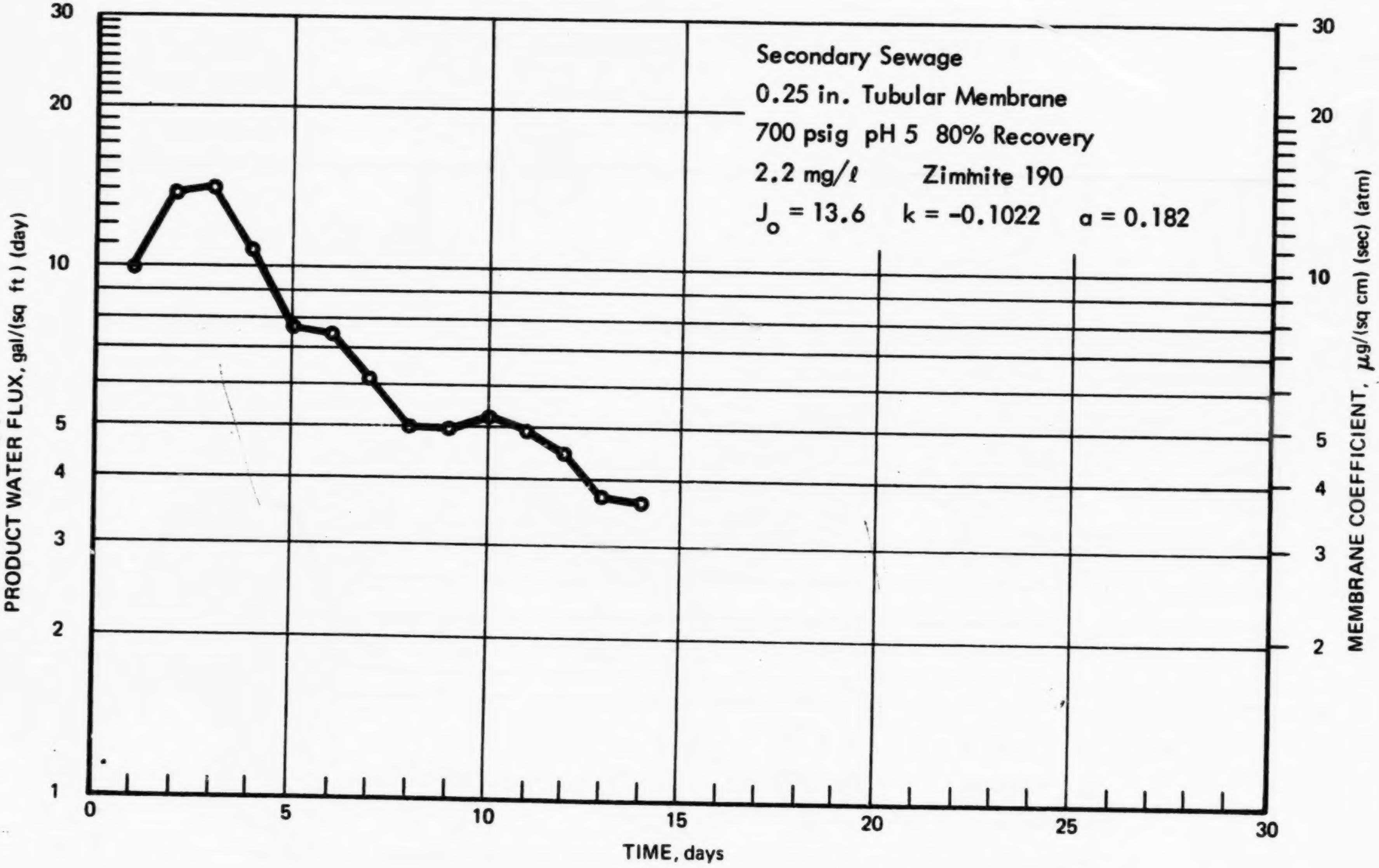

Figure 73. PRODUCT WATER FLUX, TEST 45

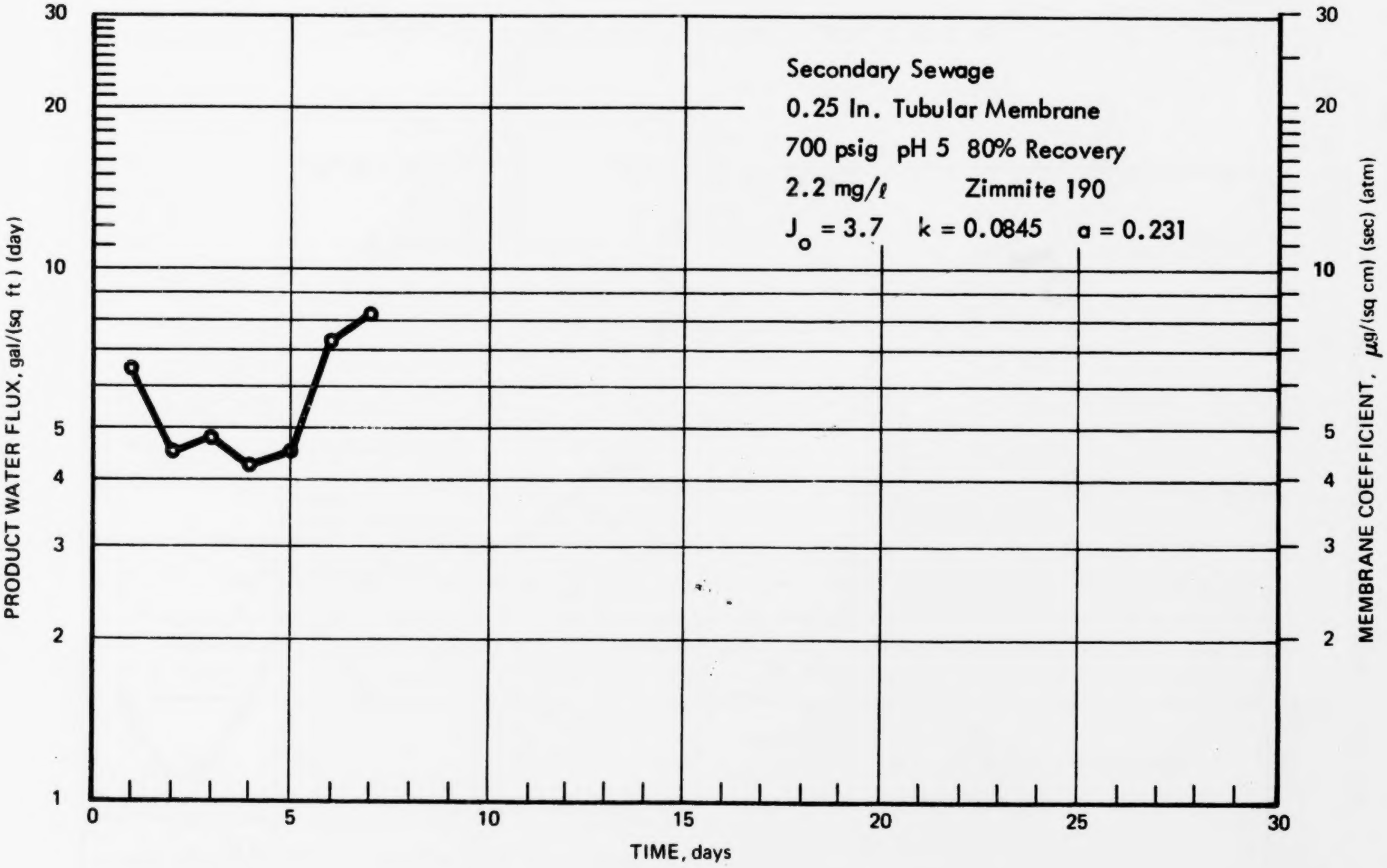

Figure 74. PRODUCT WATER FLUX, TEST 58

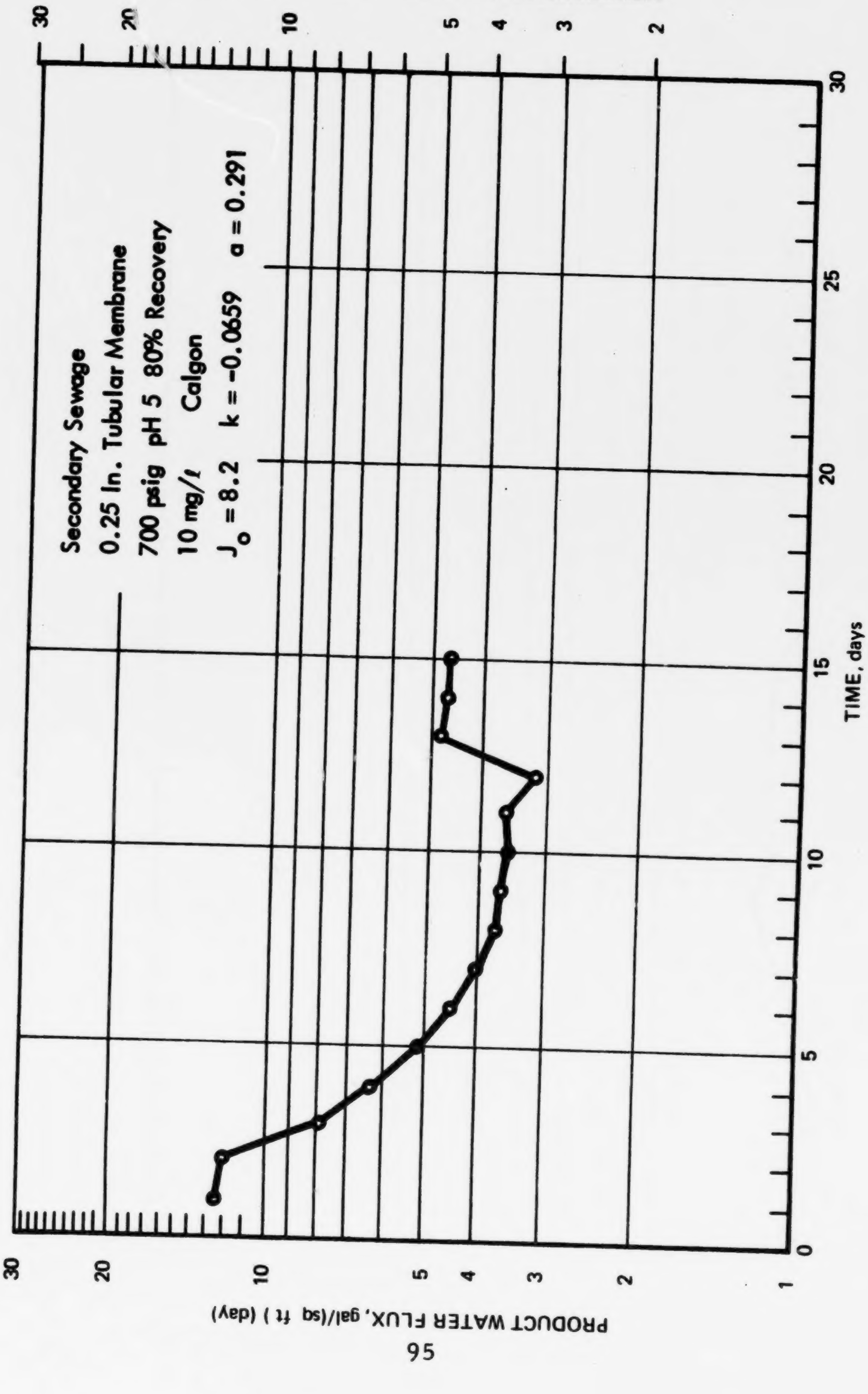

Figure 75. PRODUCT WATER FLUX, TEST 61

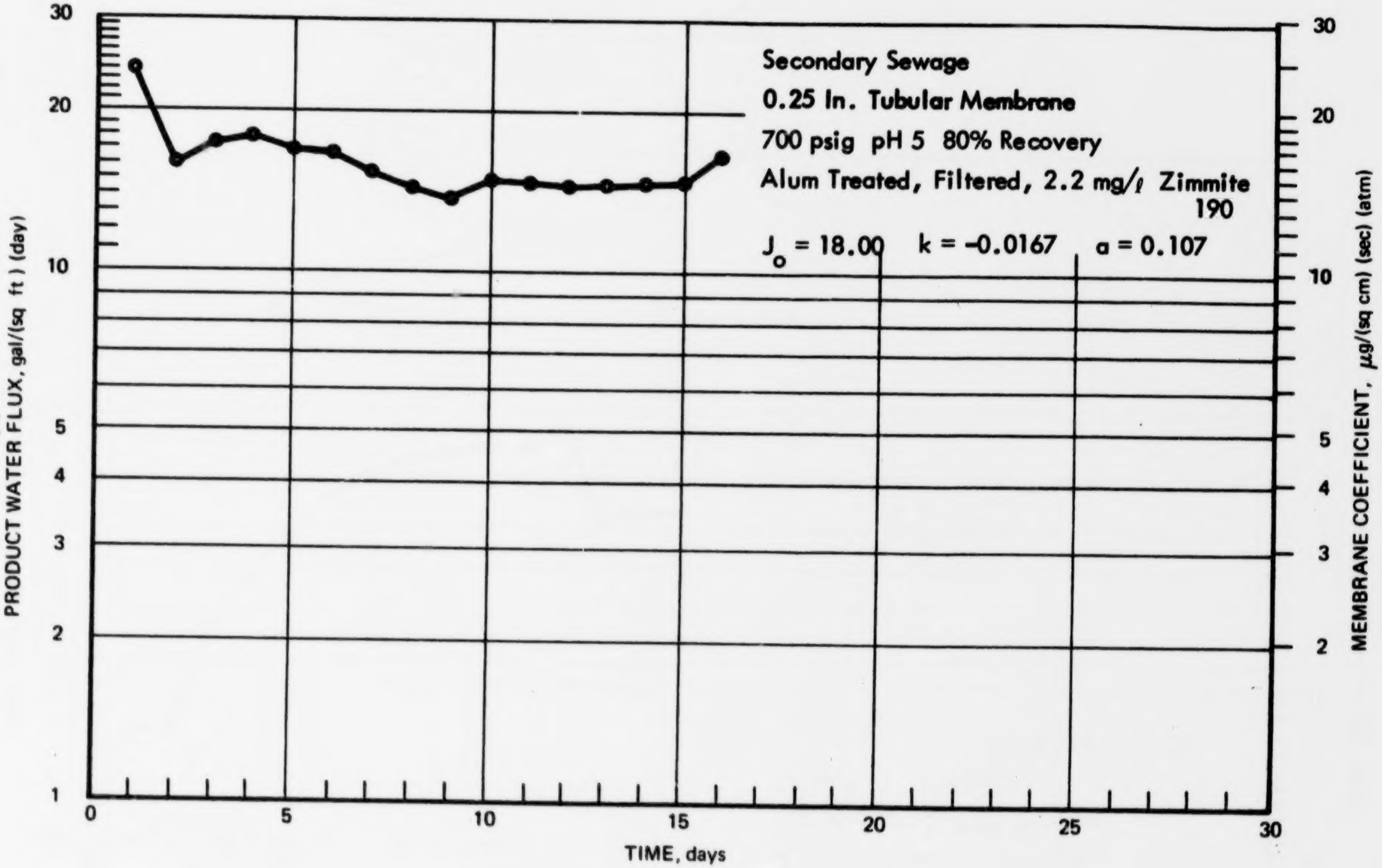

Figure 76. PRODUCT WATER FLUX, TEST 35

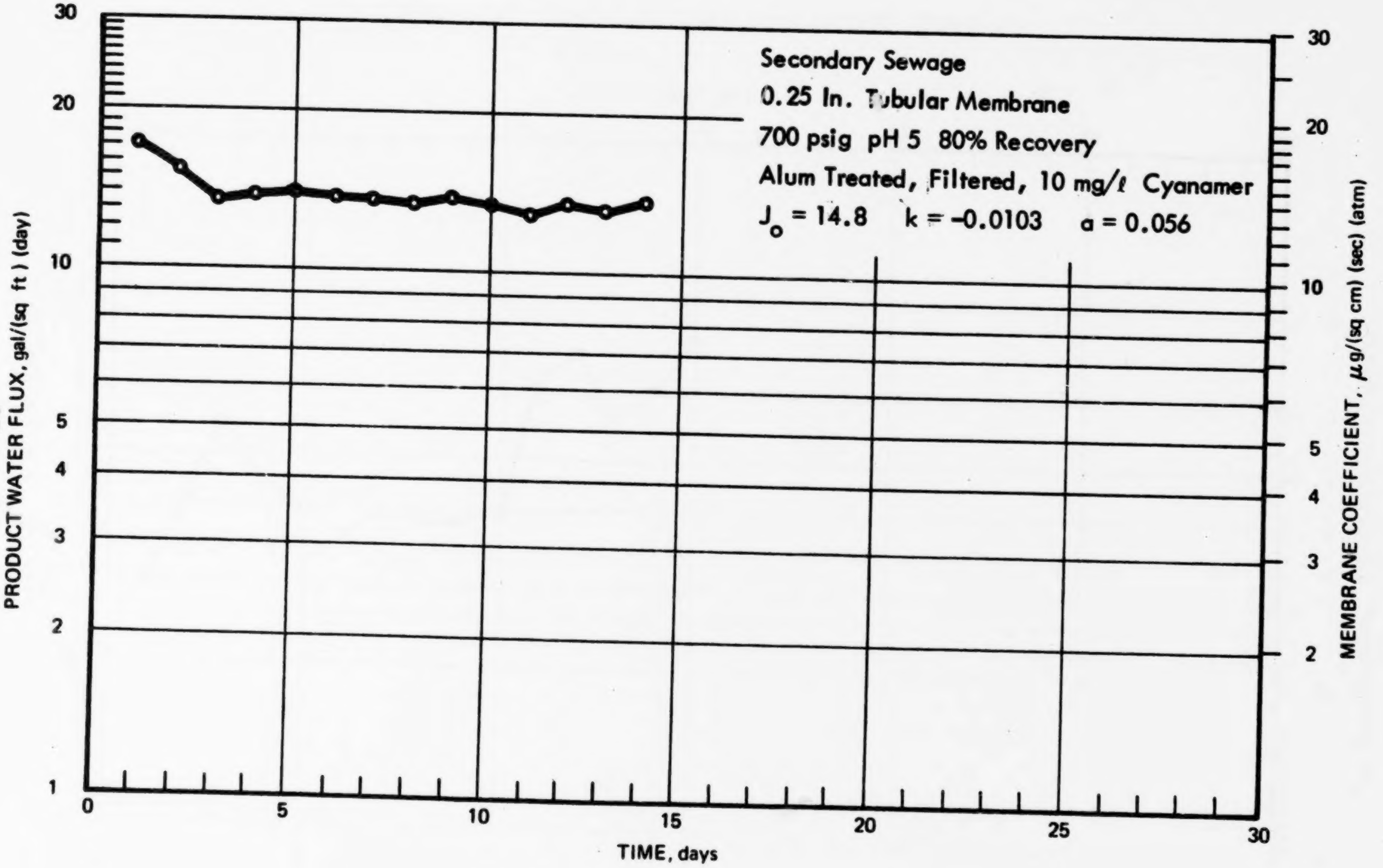

Figure 77. PRODUCT WATER FLUX, TEST 36

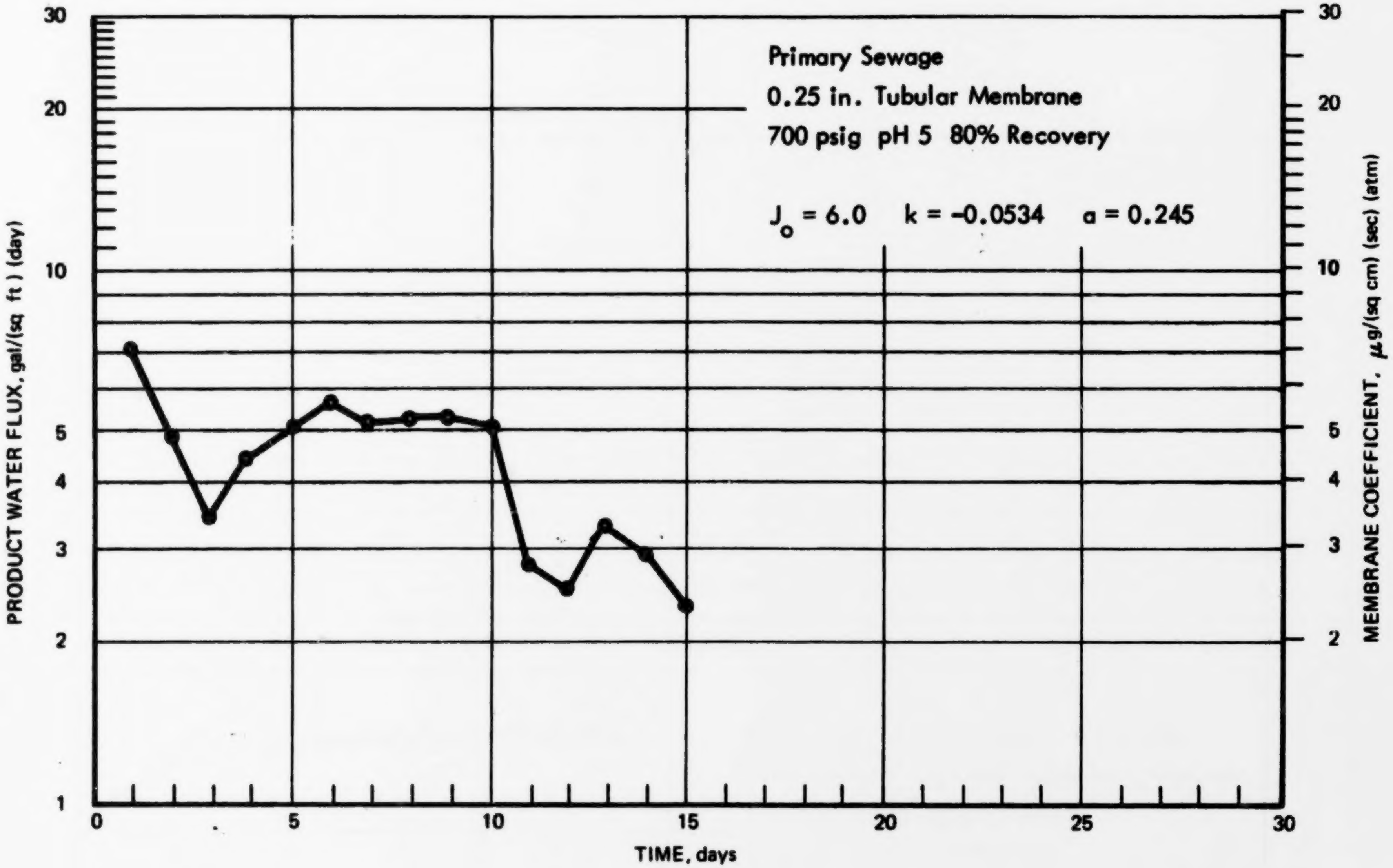

Figure 78. PRODUCT WATER FLUX, TEST 69

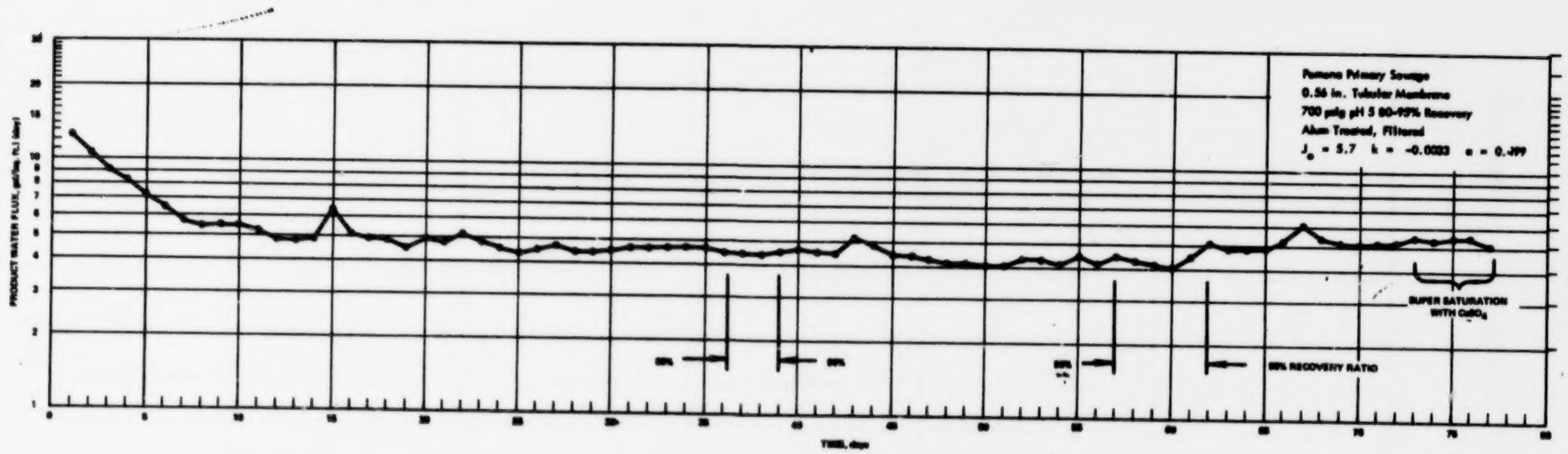

Figure 79. PRODUCT WATER FLUX, TEST 76

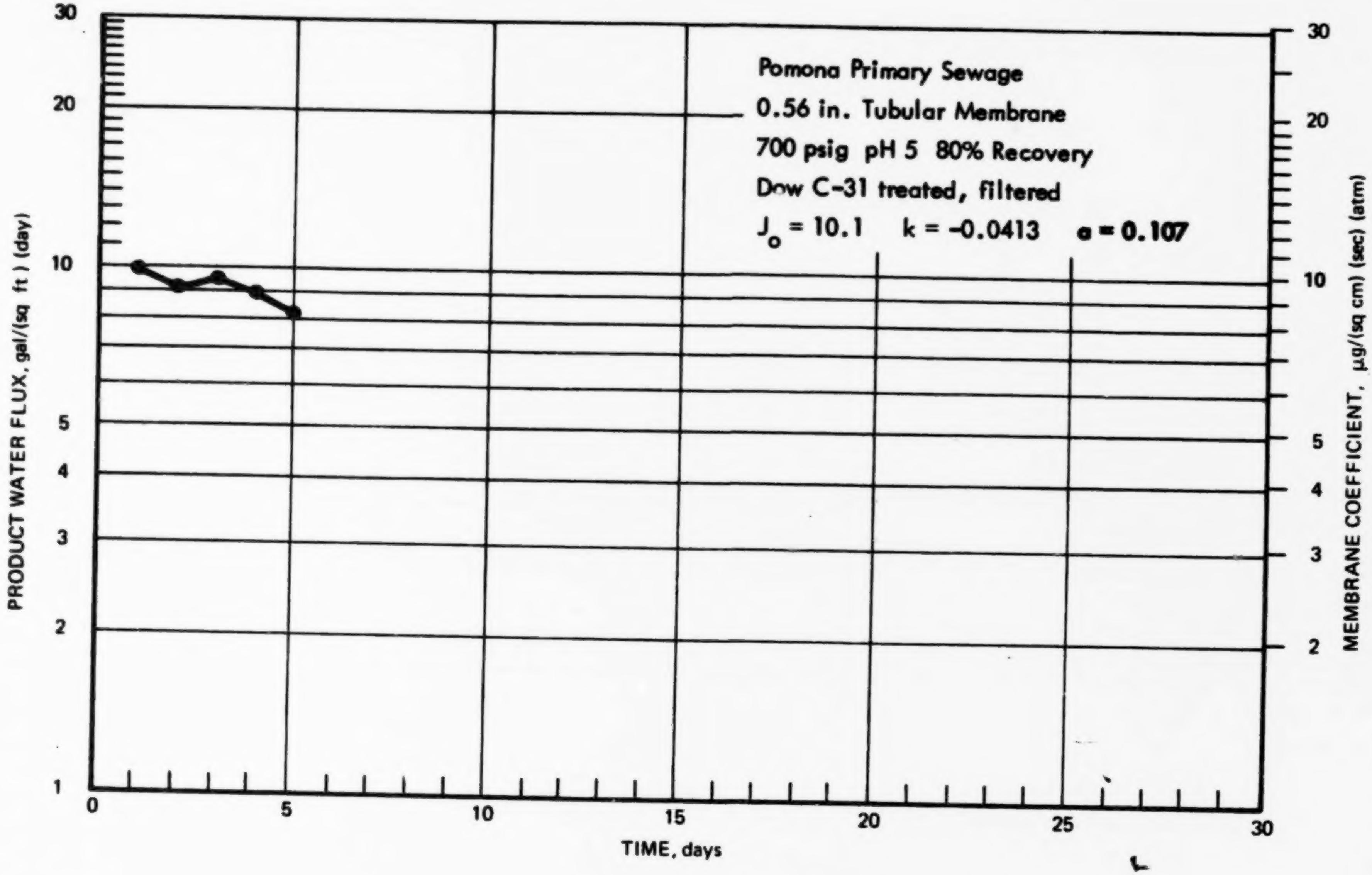

Figure 80. PRODUCT WATER FLUX, TEST 96

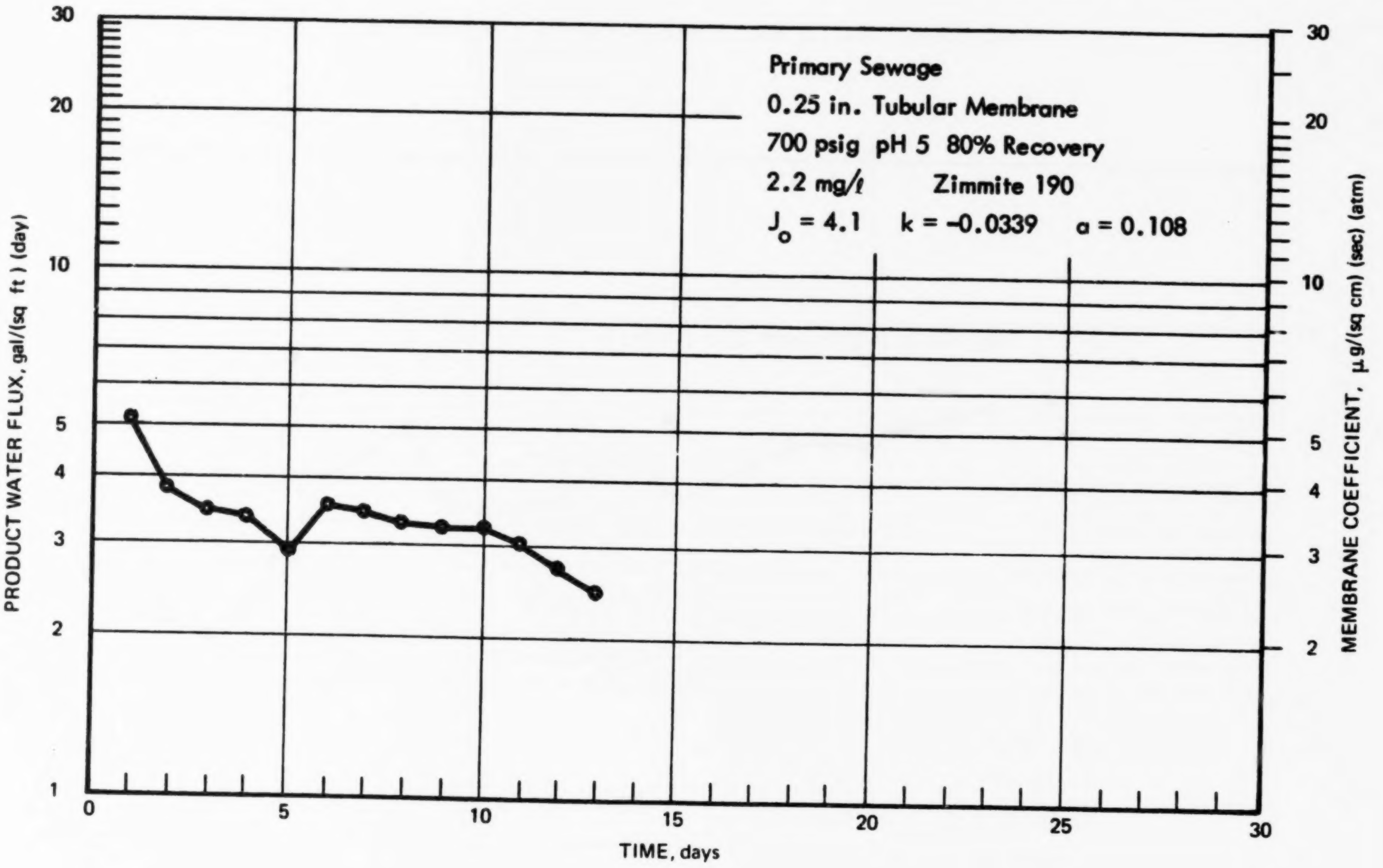

Figure 81. PRODUCT WATER FLUX, TEST 71

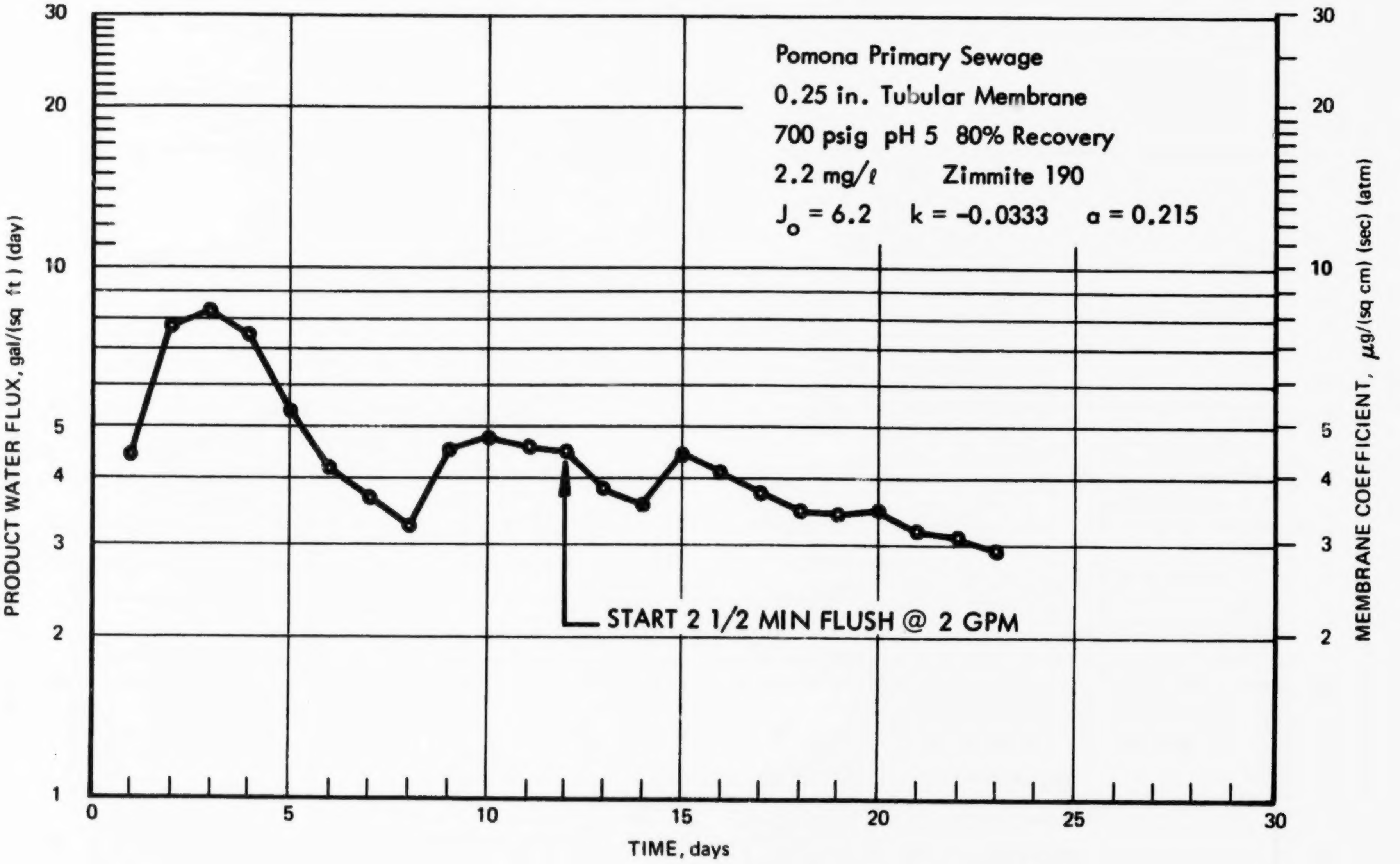

Figure 82. PRODUCT WATER FLUX, TEST 55

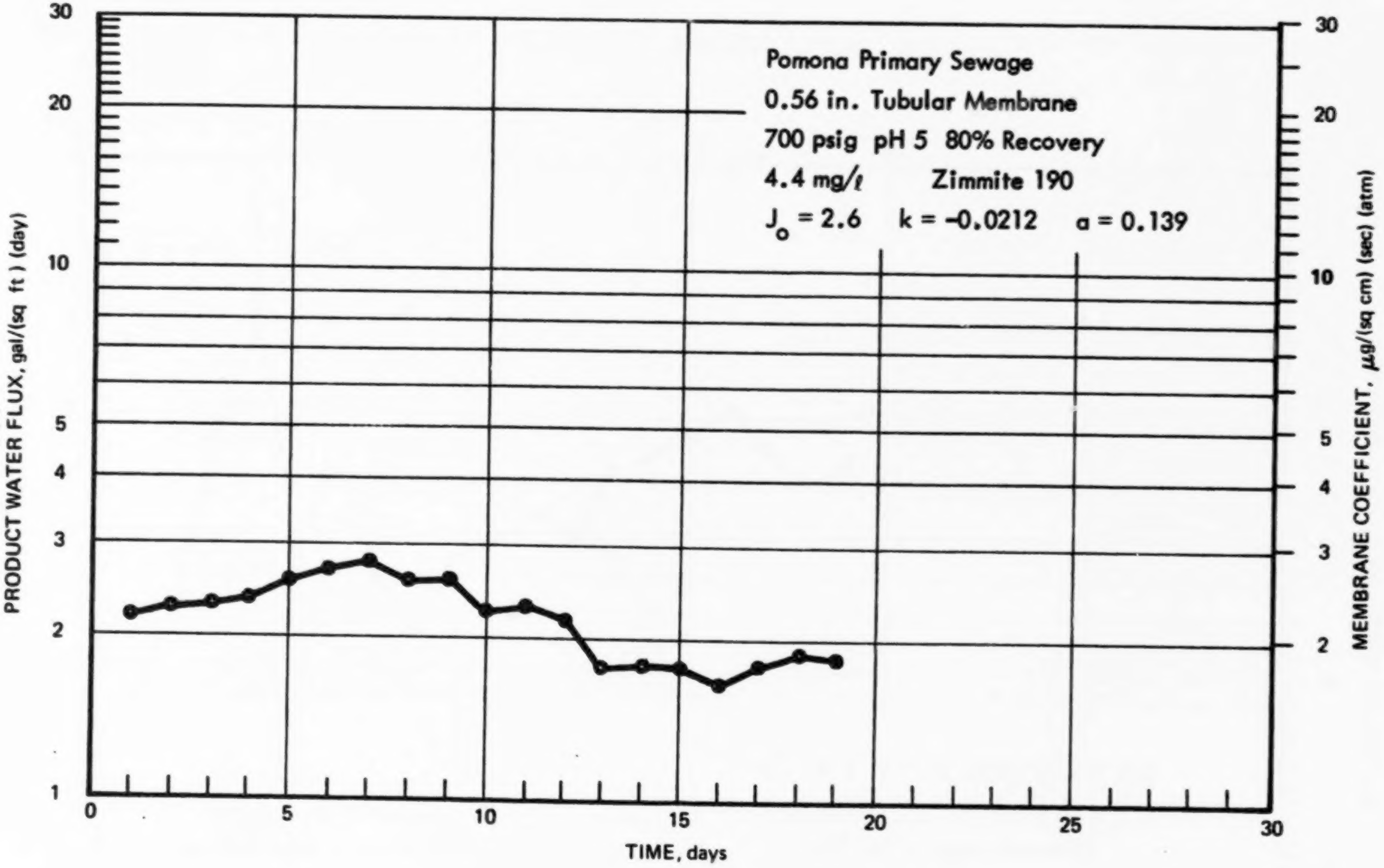

Figure 83. PRODUCT WATER FLUX, TEST 82

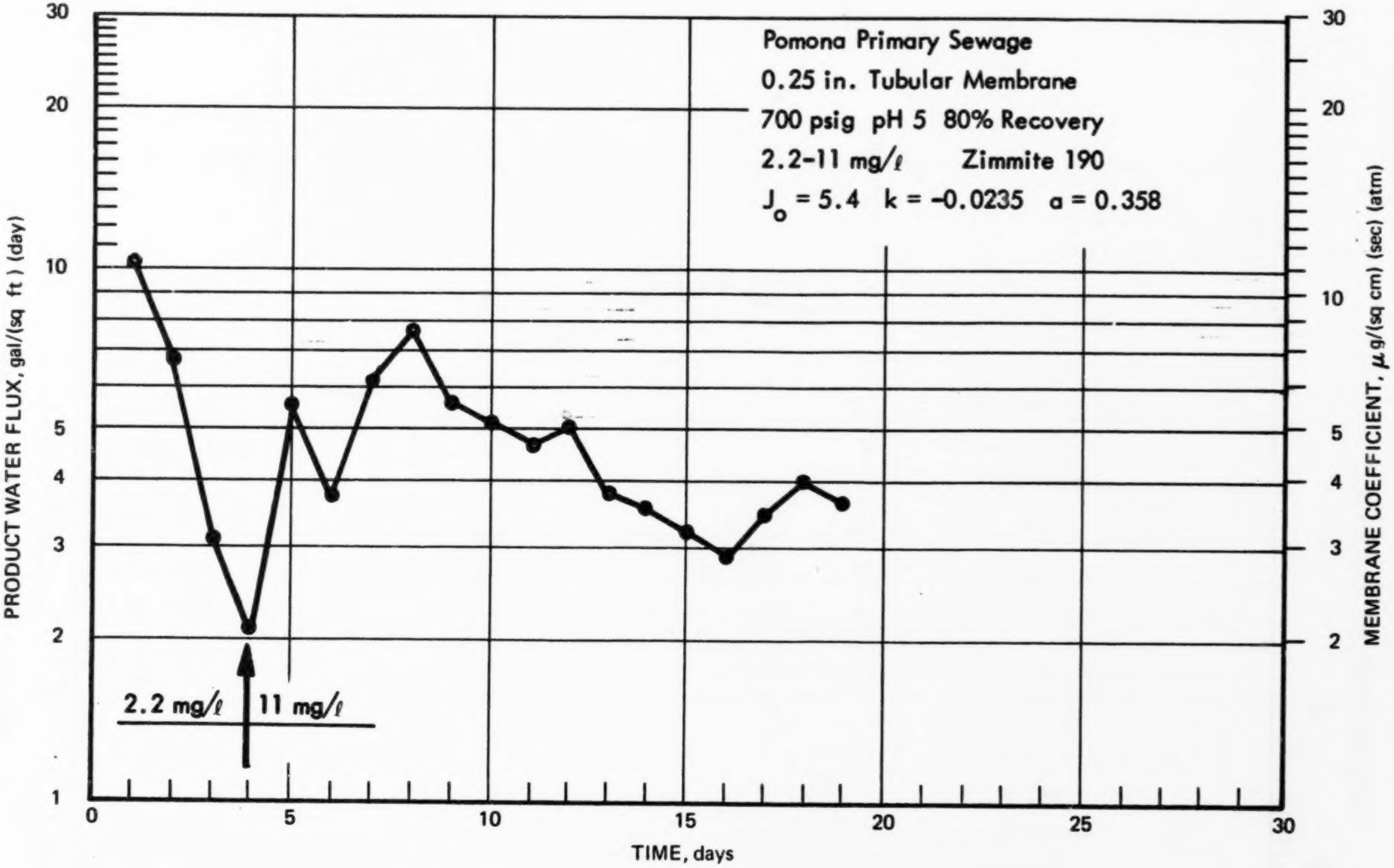

Figure 84. PRODUCT WATER FLUX, TEST 47

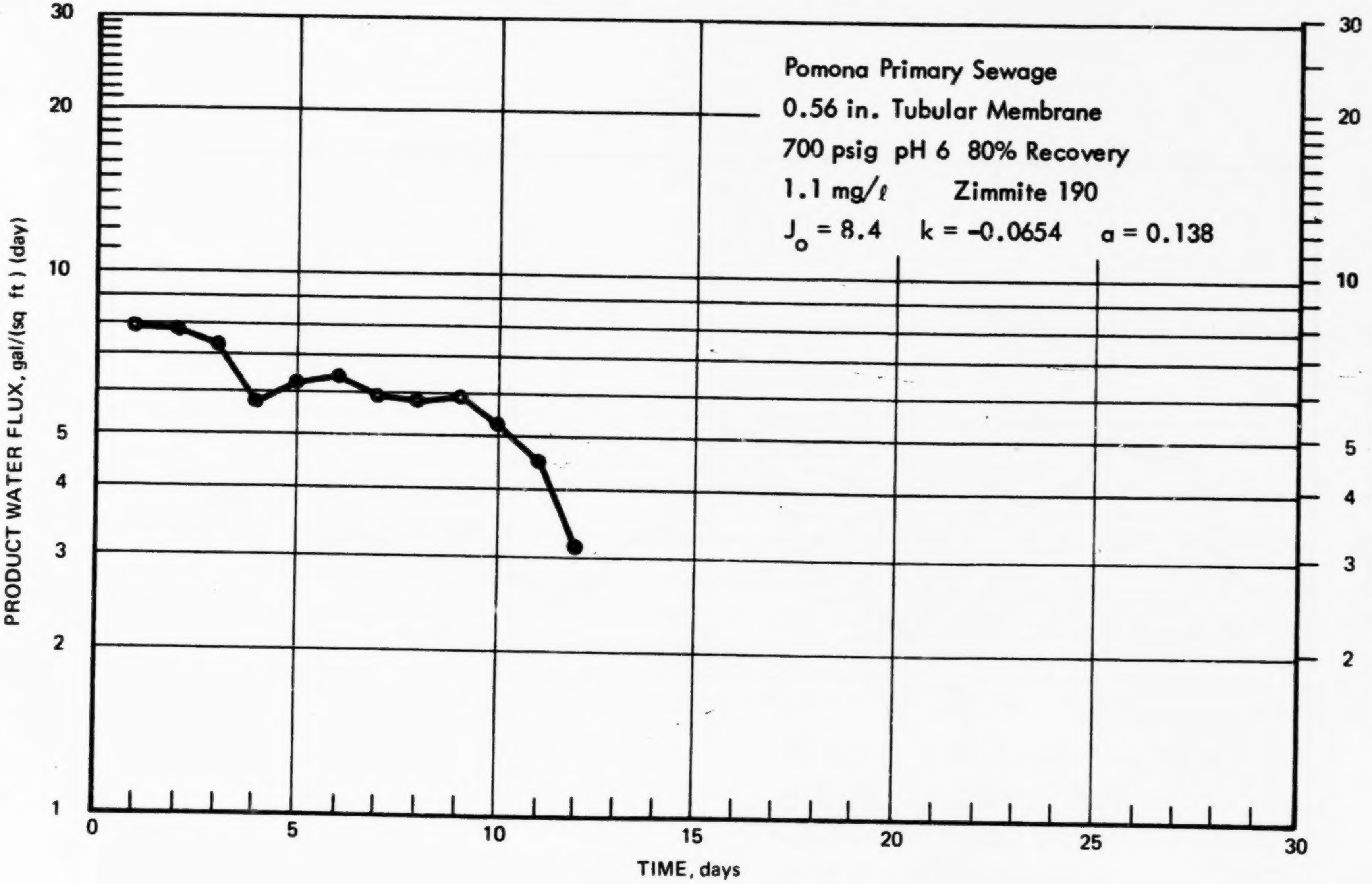

Figure 85. PRODUCT WATER FLUX, TEST 92

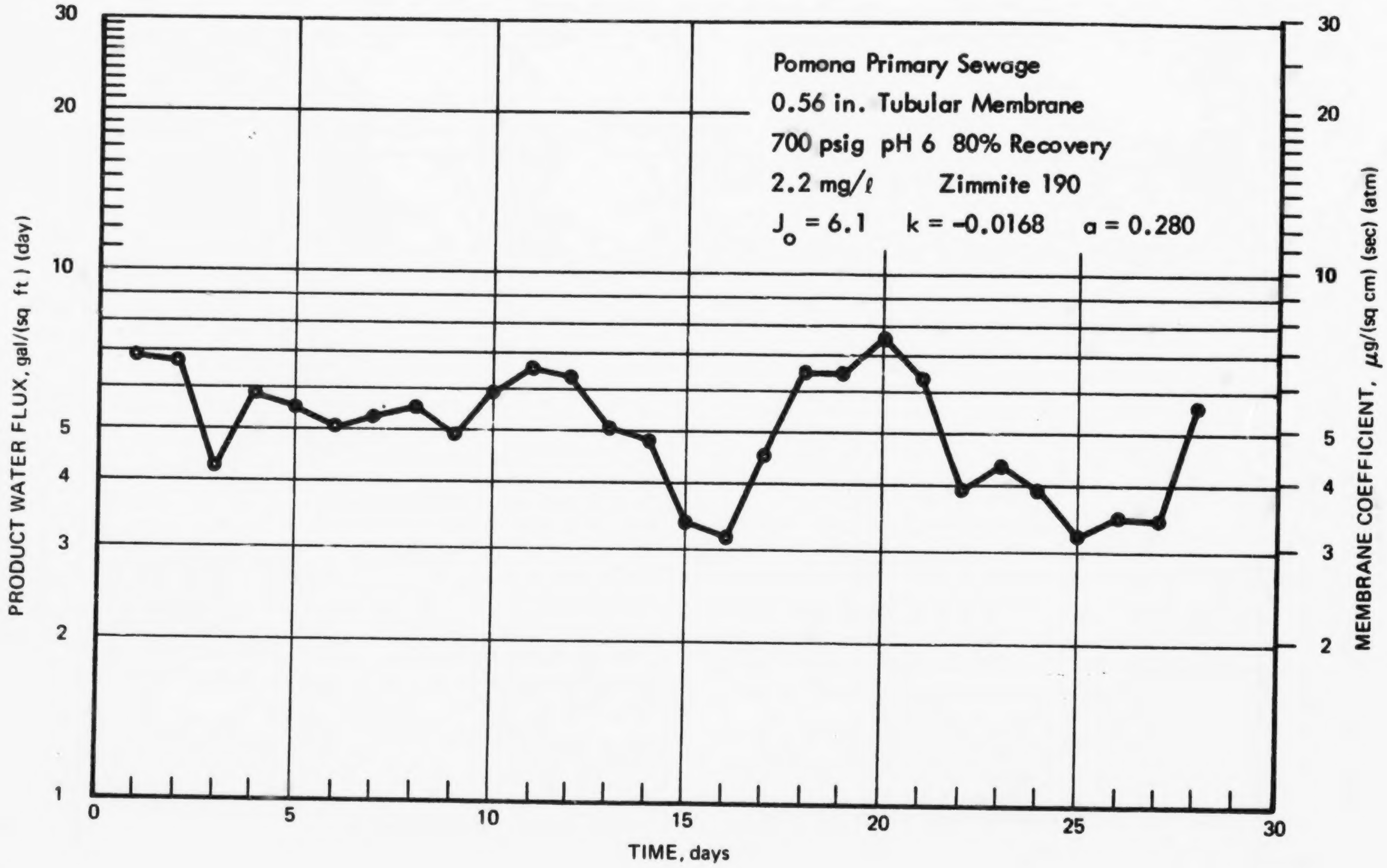

Figure 86. PRODUCT WATER FLUX, TEST 81

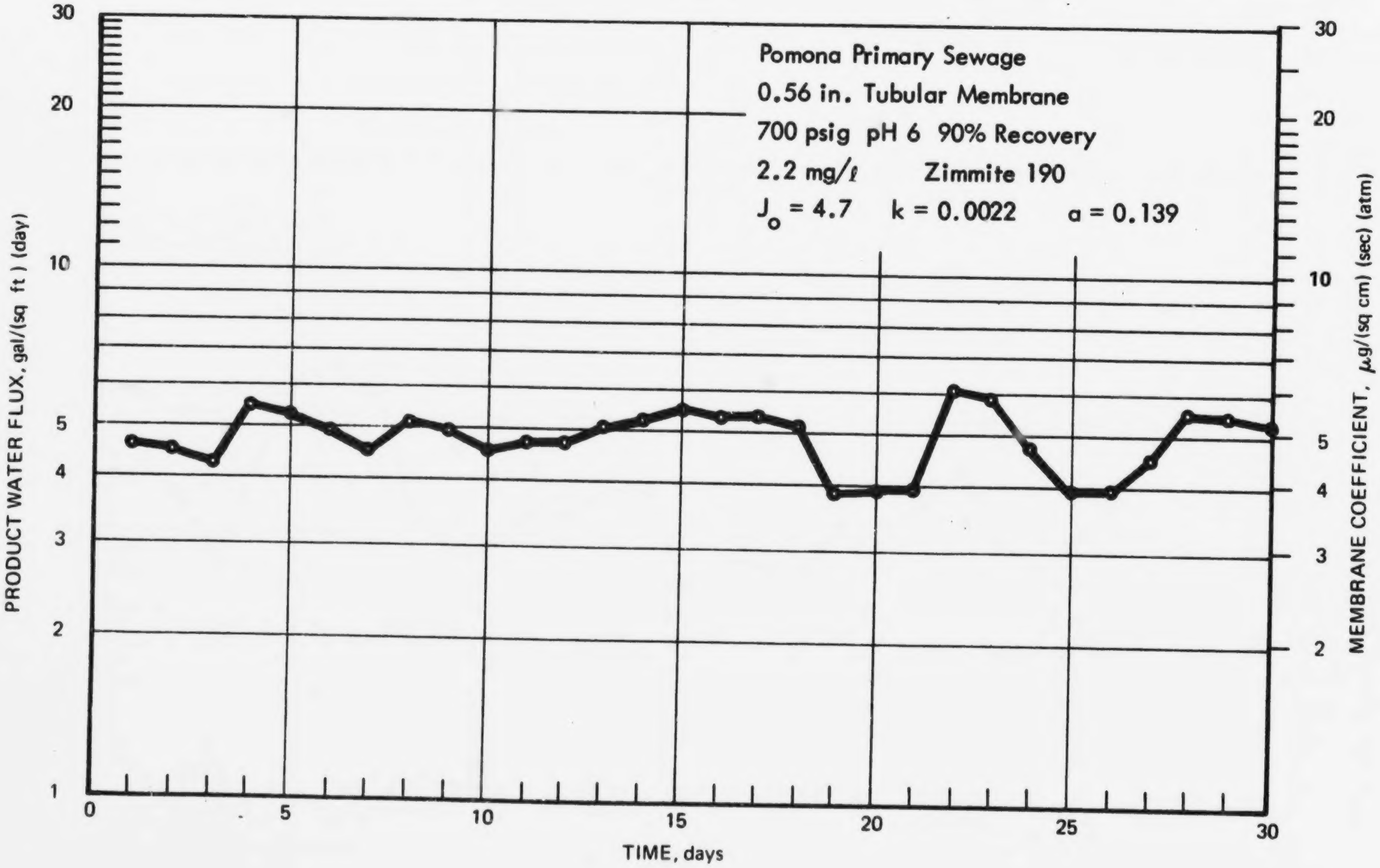

Figure 87. PRODUCT WATER FLUX, TEST 86

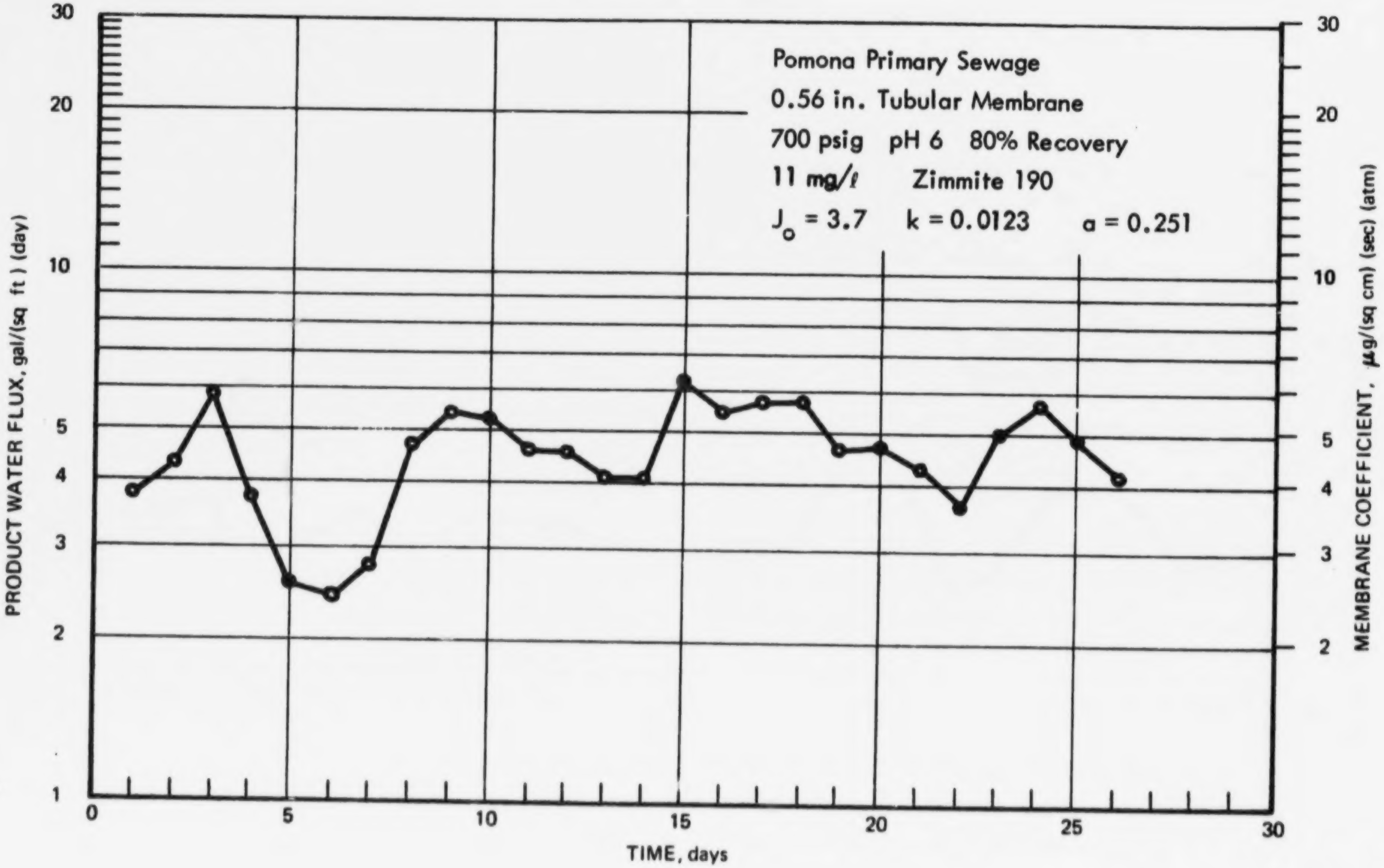

Figure 88. PRODUCT WATER FLUX, TEST 91

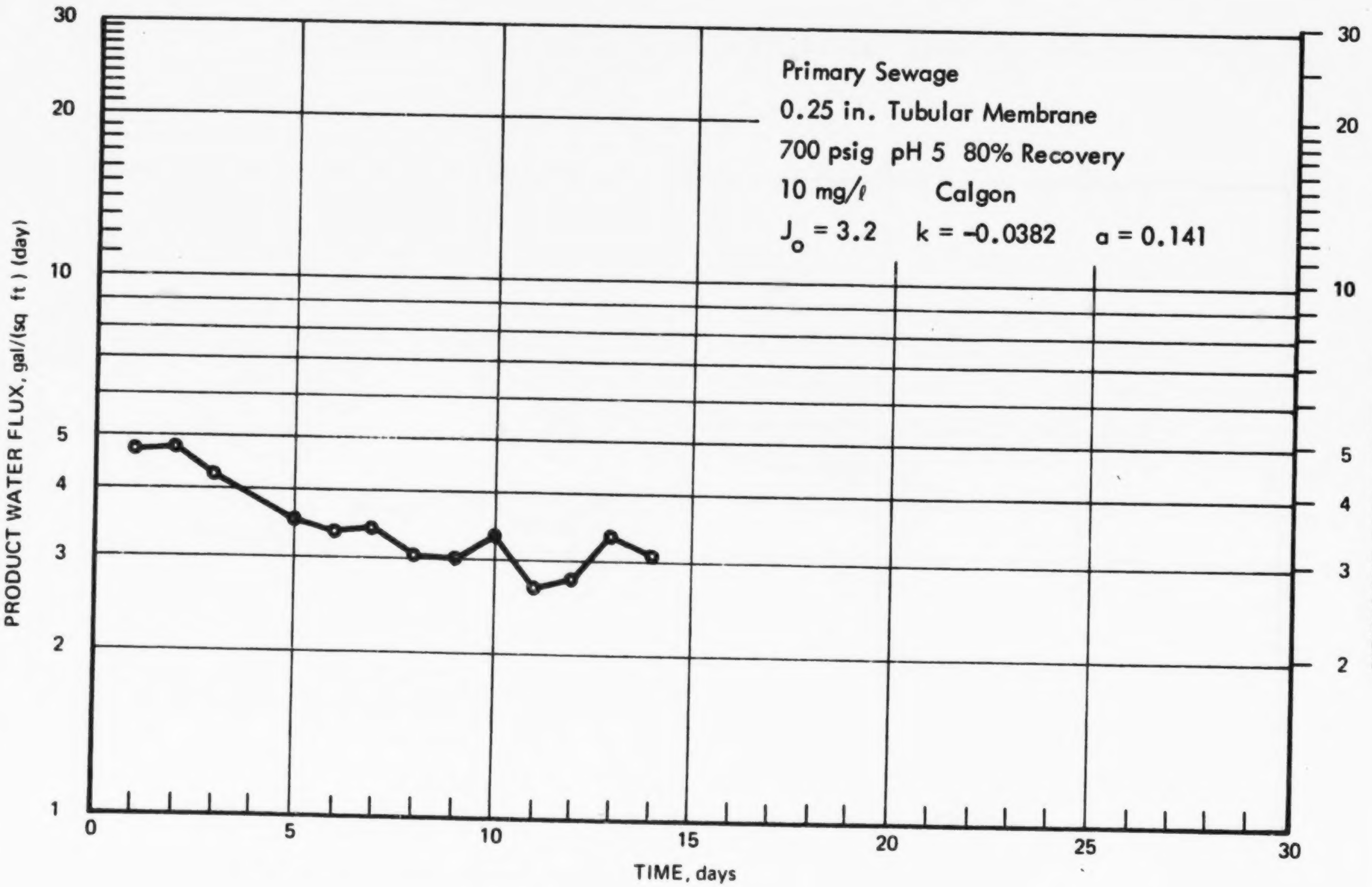

Figure 89. PRODUCT WATER FLUX, TEST 79

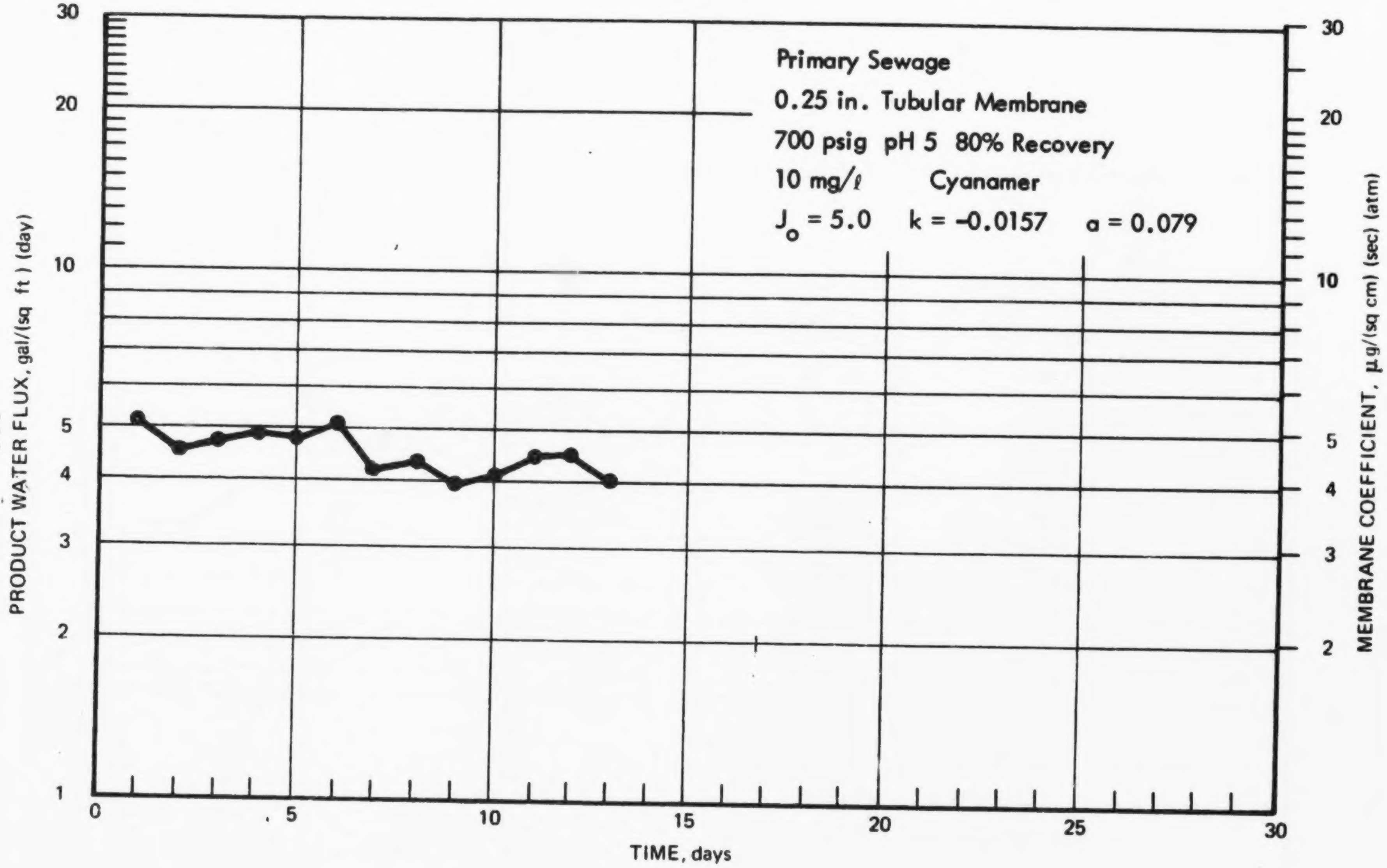

Figure 90. PRODUCT WATER FLUX, TEST 85

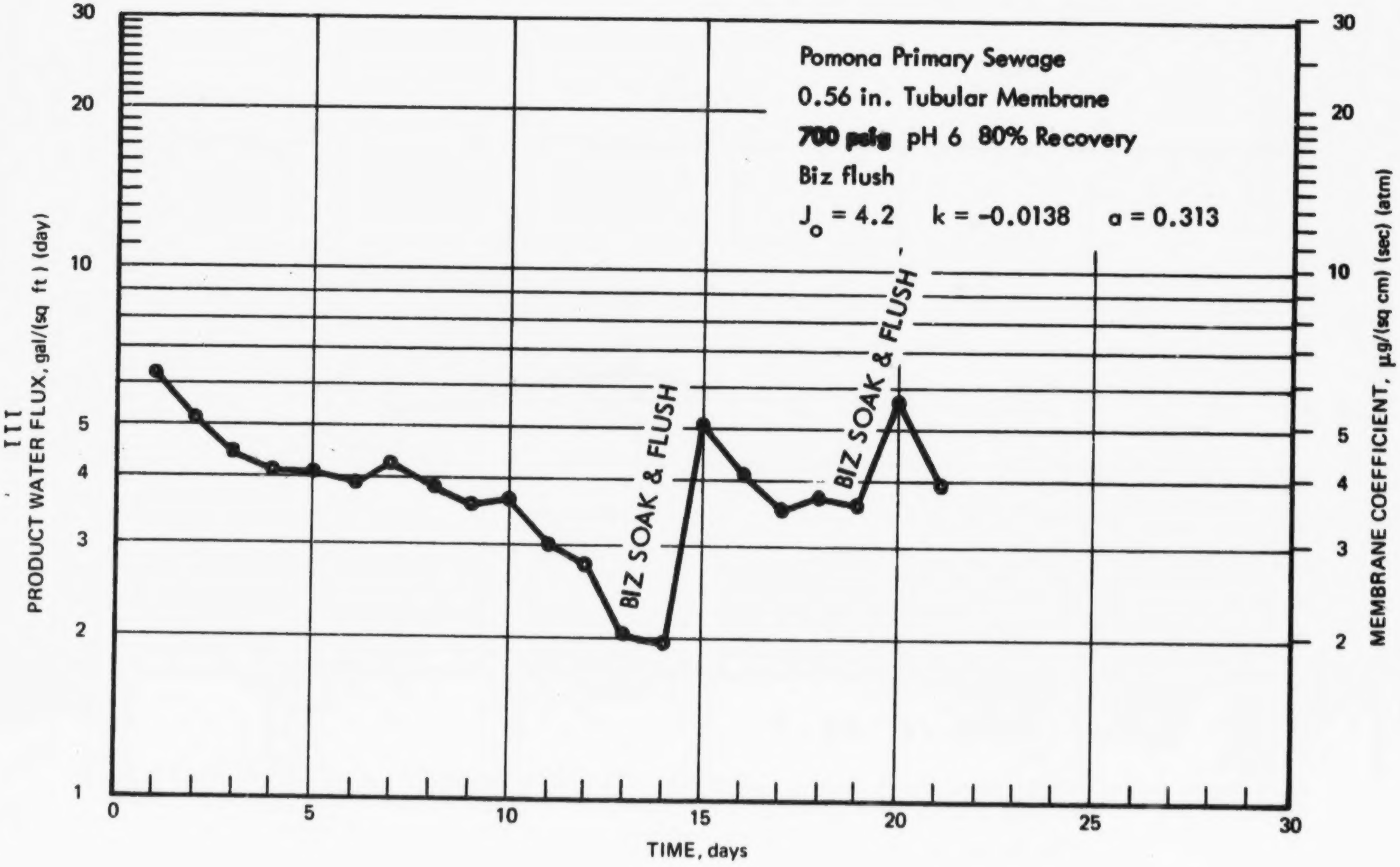

Figure 91. PRODUCT WATER FLUX, TEST 89

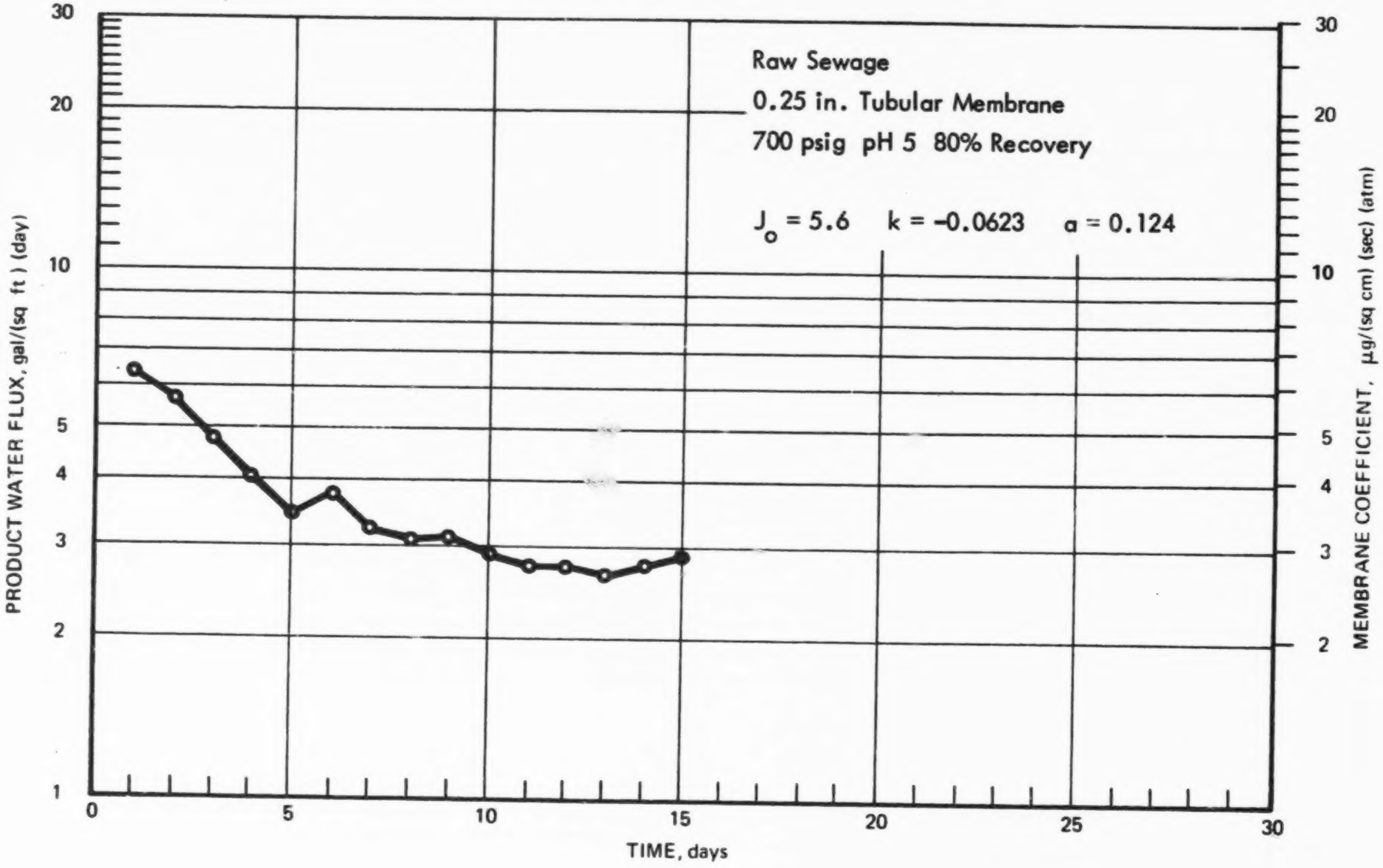

Figure 92. PRODUCT WATER FLUX, TEST 63

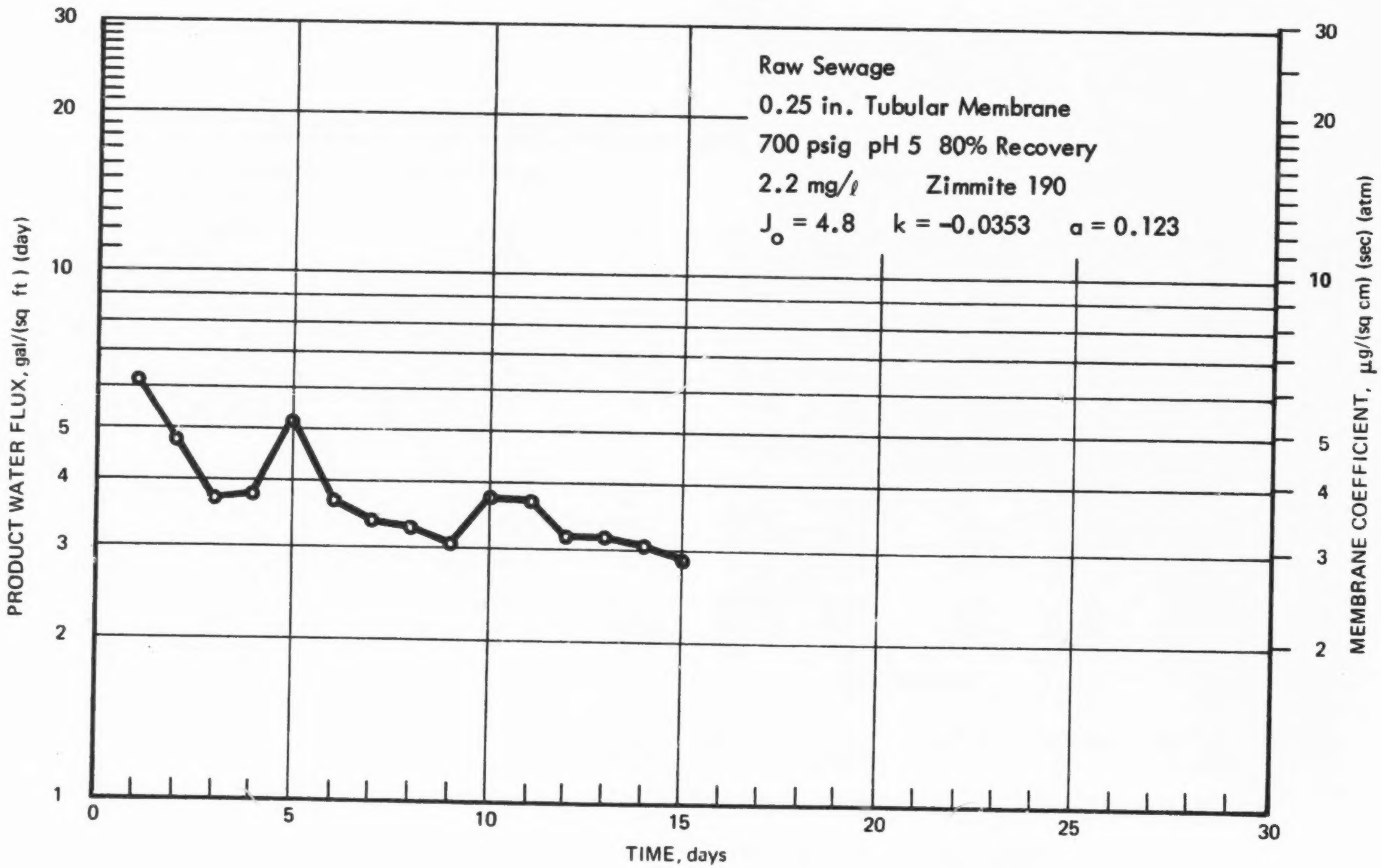

Figure 93. PRODUCT WATER FLUX, TEST 64

Table 3

AVERAGE WASTEWATER CONSTITUENT REJECTIONS AND PRODUCT WATER QUALITY FOR 68° FLAT-PLATE MEMBRANES AT 700 PSIG

	EC*	Total COD	NH_4-N	Organic N	NO_2-N	NO_3-N	Total PO_4-P	MBAS
				Rejections, %				
Pomona Wastewater								
Carbon-treated Secondary Sewage	92.0	83.6	87.3	92.0	67.4	47.0	98.3	92.5
Secondary Sewage	91.7	93.2	86.7	86.8	44.7	61.3	99.1	83.0
Primary Sewage	87.6	92.7	85.0	82.1	82.8	68.0	98.2	99.0
Fountain Valley Wastewater								
Alum-treated Secondary Sewage	85.9	78.9	79.5	70.7	89.6	23.0	93.4	90.2
Secondary Sewage	90.2	91.0	86.4	87.6	57.0	68.8	98.9	92.9
Primary Sewage	90.5	94.2	82.1	89.4	89.9	92.0	99.2	93.9
Raw Sewage	82.8	88.2	73.6	78.3	60.1	69.5	96.6	92.5
Digester Sewage	77.6	97.4	82.9	98.2	99.4	78.1	94.4	99.4
				Product Water Quality, mg/l**				
Pomona Wastewater								
Carbon-treated Secondary Sewage	193	9.16	1.86	0.330	0.015	2.28	0.40	0.52
Secondary Sewage	246	5.15	3.13	1.01	0.024	1.68	0.18	0.28
Primary Sewage	328	16.2	5.19	1.65	0.008	0.520	0.27	0.24
Fountain Valley Wastewater								
Alum-treated Secondary Sewage	483	15.4	4.47	1.46	0.001	1.27	0.072	0.12
Secondary Sewage	374	11.0	5.67	1.29	0.011	0.910	0.19	0.11
Primary Sewage	298	6.88	9.70	2.03	0.003	0.047	0.097	0.072
Raw Sewage	668	17.0	11.4	3.55	0.011	0.280	0.36	0.11
Digester Sewage	2585	151	116	10.8	0.001	2.94	9.36	0.37

---

*Electrical Conductivity, µmhos/cm at 25°C

**Adjusted to product quality of total output of plant operating at 80% recovery except Digester Sewage which is at 50% recovery.

Table 4

AVERAGE WASTEWATER CONSTITUENT REJECTIONS AND PRODUCT WATER QUALITY FOR 0.25-IN. DIAMETER TUBES AT 700 PSIG

	EC*	Total COD	NH_4-N	Organic N	NO_2-N	NO_3-N	Total PO_4-P	MBAS
				Rejections, %				
Pomona Wastewater								
Carbon-treated Secondary Sewage	88.9	90.2	88.3	92.3	93.7	67.4	98.6	94.0
Alum-treated Secondary Sewage	89.7	89.8	84.5	93.0	40.5	34.5	99.2	-
Primary Sewage	90.2	87.8	90.7	84.3	100	46.9	98.6	91.7
Fountain Valley Wastewater								
Alum-treated Secondary Sewage	85.6	86.1	79.9	77.0	88.1	24.4	92.5	93.6
Secondary Sewage	92.4	91.5	89.7	91.1	76.6	54.2	98.8	94.8
Primary Sewage	89.3	94.4	65.6	84.2	39.6	83.3	99.0	-
Raw Sewage	89.1	60.0	77.1	89.7	92.6	51.9	98.2	94.1
				Product Water Quality, mg/l**				
Pomona Wastewater								
Carbon-treated Secondary Sewage	204	8.15	2.33	0.250	0.000	0.170	0.17	0.030
Alum-treated Secondary Sewage	237	4.31	1.49	0.640	0.018	6.14	0.060	-
Primary Sewage	232	21.3	1.71	1.65	0.000	0.990	0.094	0.19
Fountain Valley Wastewater								
Alum-treated Secondary Sewage	452	12.4	6.08	1.51	0.000	1.27	0.051	0.072
Secondary Sewage	245	13.5	3.06	0.660	0.011	0.510	0.12	0.071
Primary Sewage	245	6.23	6.07	1.55	0.032	0.092	0.057	-
Raw Sewage	523	84.7	5.59	2.00	0.004	0.550	0.12	0.080

---

*Electrical Conductivity, µmhos/cm at 25°C

**Adjusted to product quality of total output of plant operating at 80% recovery

Table 5

AVERAGE WASTEWATER CONSTITUENT REJECTIONS AND PRODUCT WATER QUALITY FOR 0.56-IN. DIAMETER TUBES AT 700 PSIG

	EC*	Total COD	NH_4-N	Organic N	NO_2-N	NO_3-N	Total PO_4-P	MBAS
				Rejections, %				
Pomona Wastewater								
Alum-treated Secondary Sewage	93.3	96.0	97.7	100	11.1	41.2	98.4	-
Alum-treated Primary Sewage	93.2	79.1	87.4	57.7	49.8	36.5	95.1	-
Primary Sewage	95.3	92.4	94.7	62.5	39.8	55.1	99.2	-
				Product Water Quality, mg/l**				
Pomona Wastewater								
Alum-treated Secondary Sewage	101	1.66	0.270	0.000	0.036	4.69	0.094	-
Alum-treated Primary Sewage	166	18.3	1.01	1.67	0.015	2.54	0.088	-
Primary Sewage	86.1	10.5	1.02	1.56	0.041	1.24	0.100	-

---

[*] Electrical Conductivity, µmhos/cm at 25°C

[**] Adjusted to product quality of total output of plant operating at 80% recovery

Table 6

AVERAGE WASTEWATER CONSTITUENT REJECTIONS AND PRODUCT WATER QUALITY FOR 44° FLAT-PLATE MEMBRANES AT 200 PSIG

	EC*	Total COD	NH_4-N	Organic N	NO_2-N	NO_3-N	Total PO_4-P	MBAS
				Rejections, %				
Pomona Wastewater								
Carbon-treated Secondary Sewage	79.1	77.1	48.5	97.4	55.9	48.8	99.4	92.9
Secondary Sewage	77.1	82.5	85.5	88.7	28.7	34.3	94.2	93.6
Primary Sewage	77.6	91.0	75.0	82.6	74.8	53.6	94.4	-
Fountain Valley Wastewater								
Alum-treated Secondary Sewage	78.3	79.9	68.3	67.3	0.0	18.5	94.1	87.0
				Product Water Quality, mg/l**				
Pomona Wastewater								
Carbon-treated Secondary Sewage	371	4.66	3.78	0.058	0.064	1.57	0.13	0.071
Secondary Sewage	372	7.11	1.99	0.990	0.012	4.98	0.97	0.100
Primary Sewage	455	22.5	5.20	1.51	0.011	0.860	0.98	-
Fountain Valley Wastewater								
Alum-treated Secondary Sewage	508	12.0	4.74	0.790	0.016	0.092	0.068	0.14

---

*Electrical Conductivity, μmhos/cm at 25°C

**Adjusted to product quality of total output of plant operating at 80% recovery of higher product water flux. The 0.56-in. diameter tubular membranes produced high rejections for most ions except the organic and oxidized forms of nitrogen.

The concentrations of the various wastewater constituents in the product water, listed in Tables 3, 4, 5, and 6, have been adjusted from the observed values to correspond to concentrations that would be expected in a nonrecirculating reverse osmosis plant operating over the complete range of product water recovery ratios from zero at the influent to the maximum (in this case, 80 percent) at the discharge. The calculated modifications were based on the assumption that the individual constituent rejections are the same throughout the plant. The equations used to determine overall plant performance were

$$(\text{Product Concentration})_{\text{plant}} = f_1\ (\text{Product Concentration})_{\text{lab}}$$

where

$$f_1 = \frac{(1-R)^r - (1-R)}{R(1-r)}$$

$$R = \left[\frac{\text{Total Quantity Product Water}}{\text{Total Quantity Feed Water}}\right]_{\text{plant}}$$

$$r = 1 - \left[\frac{\text{Average Product Concentration}}{\text{Average Wastewater Concentration}}\right]_{\text{plant}}$$

$$r = 1 - \left[\frac{\text{Product Concentration}}{\text{Wastewater Concentration}}\right]_{\text{lab}}$$

Section V

DISCUSSION OF RESULTS

In this program many tests were conducted under a wide variety of operating conditions that are coupled by complex, and often unknown, inter-relationships. To separate the effects of the various parameters within the constraints provided by the schedule of laboratory testing, pertinent tests have been selected and the results or data points smoothed for clarity and easier comparison. Actual data points are presented in the preceding section.

A comparison is made in Figure 94 of the product water fluxes obtained with the various types of sewage feeds under the standard control test conditions. In all cases except one, higher quality feed water produced higher product water fluxes. The long term, stabilized fluxes obtained with primary and raw sewages appear to be identical at 2 gal/(sq ft)(day). The major difference between raw and primary sewages is the absence of gross settleable solids in the primary sewage, indicating that perhaps these materials are not a critical factor in membrane fouling or at least product water flux decline.

The magnitude of the stabilized product water flux appears to be quite dependent on the feed water quality. Carbon-treated secondary sewage produced 18 gal/(sq ft)(day) with new, clean equipment and relatively high-quality feed water and 8.5 gal/(sq ft)(day) with used equipment and relatively low-quality feed water; whereas digester supernatant fouled the membrane beyond hope of ascertaining the long-term flux. The relative absence of product water flux decline after an initial period of several weeks without any special pretreatment of the sewages suggests that treatment of the various sewages by reverse osmosis at reasonably high levels of flux may be feasible without the use of additive chemicals other than acid.

Although the sewages used in this program were from two different sources and had quite different characteristics, no difference in reverse osmosis performance as a consequence was apparent. As an example, secondary sewage from Pomona was, except for nitrate, total phosphate, and MBAS (all relatively low-concentration constituents), markedly superior in quality to the winter-season secondary sewage from Fountain Valley; yet typical results obtained with these two feeds, (cf. Figures 20 and 21) are not noticeably dissimilar. For this reason no distinction has been made between feed water sources in the analysis of performance data.

TEST-CELL GEOMETRY

The greater part of the test data reveal little difference in product water flux decline as a consequence of different test-cell or membrane geometry. Essentially stable fluxes were observed with both the flat-plate

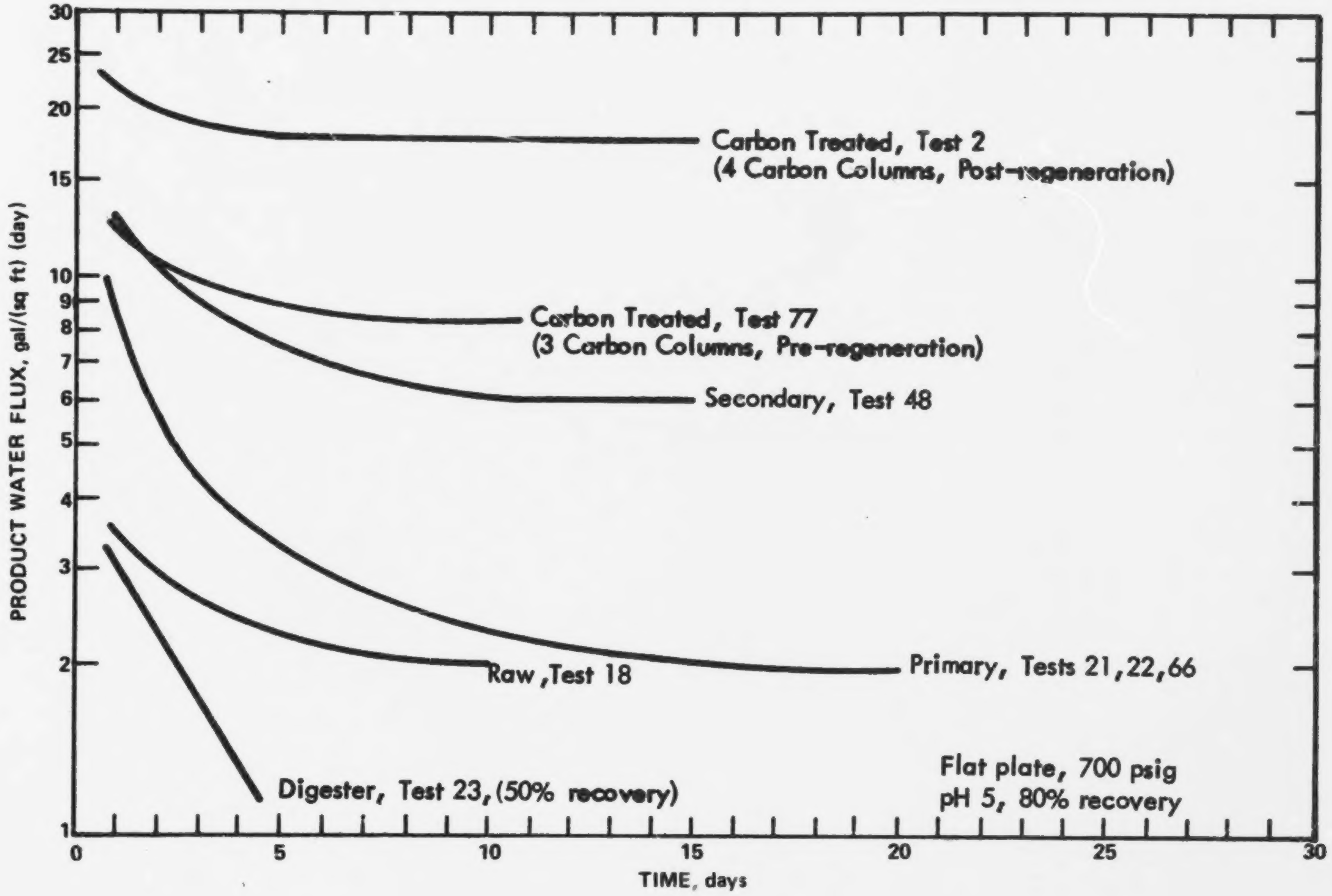

Figure 94. EFFECTS OF FEED WATER TYPE ON PRODUCT WATER FLUX

and tubular test cells and most feed waters. Where comparisons can be made under nearly similar operating conditions (cf. Figures 44 and 86, 47 and 83, and 16 and 68, for example), the flat-plate test cells provided only slightly greater product water fluxes and flux declines in most but not all cases. The higher flux magnitudes exhibited by the flat-plate membranes are in part or wholly due to their inherently greater product water flux capability. These comparisons moreover are made more difficult by the fact that the tubular units were operated at a Reynolds number of 5,000 and the flat-plate test cells were operated at a nominal Reynolds number of 3,000. The lower value was selected to correspond to the standardized test-cell conditions representative of field-scale desalination of sea water and brackish water with flat-plate reverse osmosis units, whereas the larger number was chosen to provide turbulence outside of the transition region. Operation of flat-plate units at higher flow rates and concomitantly higher Reynolds numbers are not practical due to excessive pressure losses across the membrane stacks.

One particular type of feed water, however, did produce results highly favorable to the tubular membranes and is stressed herein because of its potential in reverse osmosis processing of municipal wastewater.

Figure 95 presents the observed behavior of the flat-plate test cells and both the 0.25- and 0.56-in. diameter tubular membranes with alum-treated, sand-filtered secondary sewage, which was the only feed water that provided a noticeable distinction between the test-cell geometry. Not only are the differences in product water flux declines sizable, but the sheet membranes which provide a greater flux with brackish water produced a lesser product water flux than did the tubular membranes. Thick deposits of calcium sulfate were found on the sheet membranes while far fewer deposits of an unidentified material lined the tubular membranes. These observed differences in performance between the flat-plate and tubular test cells are believed to be manifestations only of the greatly different flow conditions and turbulence obtained in the two test apparatus.

OPERATING PRESSURE

Solids-bearing sewages--primary and secondary sewage--quickly bring out the differences in membrane performance at high and low pressures. Figure 96 compares product water fluxes between the 68° membrane at 700 and 200 psig, which demonstrated that the flux decline resulting from 700 psig operation was in excess of that obtaining with 200 psig. Tests conducted on both Zimmite 190-treated primary sewage and alum-treated, sand-filtered secondary sewage again reveal that the greater flux decline occurred at 700 psig, as shown in Figure 97.

The 44° membrane has no apparent characteristic different from the 68° membrane that would account for greater flux stability with solids-bearing sewages at low-pressure operation, other than the pressure itself. One explanation for this observation involves the layer of materials that

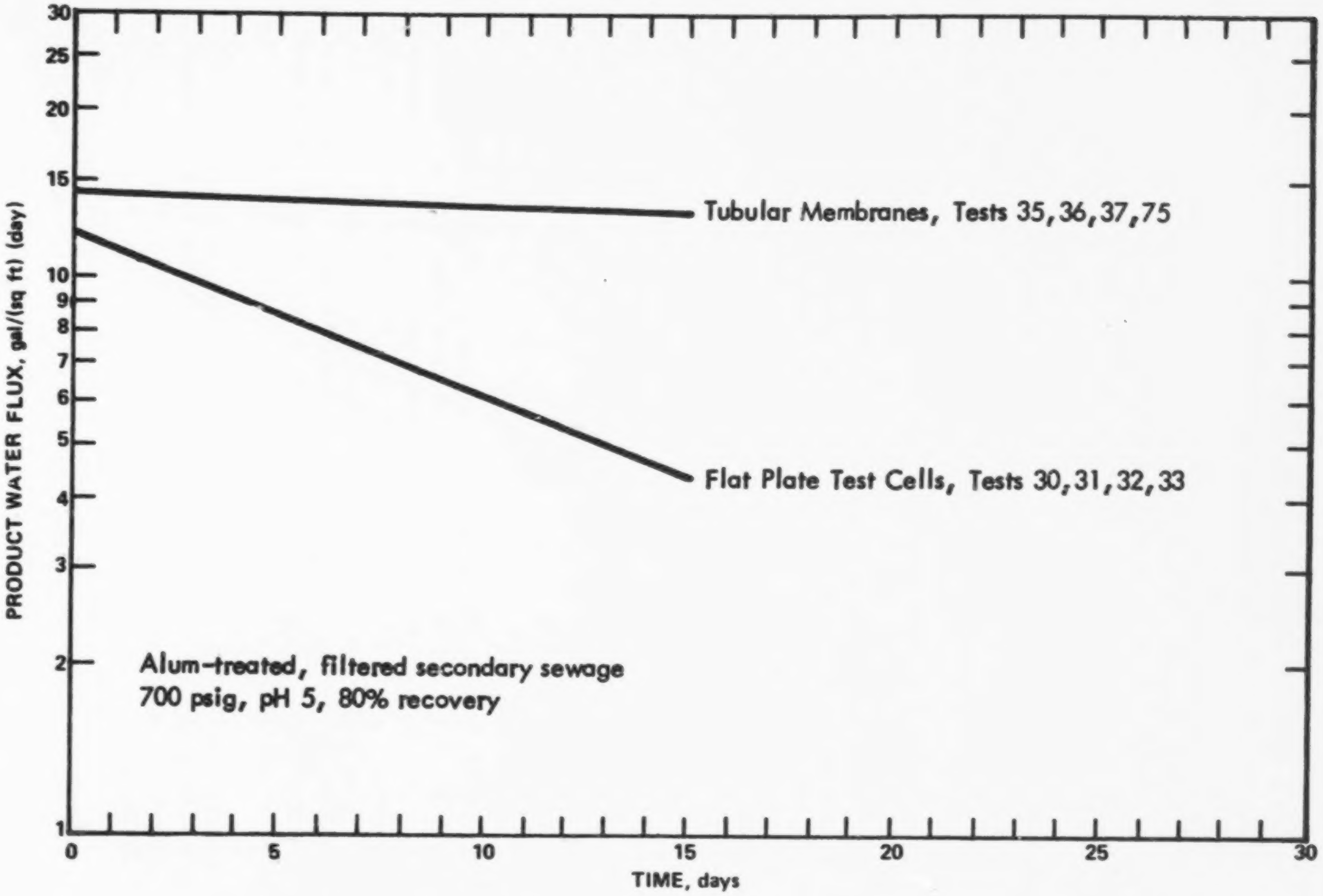

Figure 95. COMPARISON BETWEEN TEST-CELL GEOMETRY AND TYPICAL PRODUCT WATER FLUX DECLINE

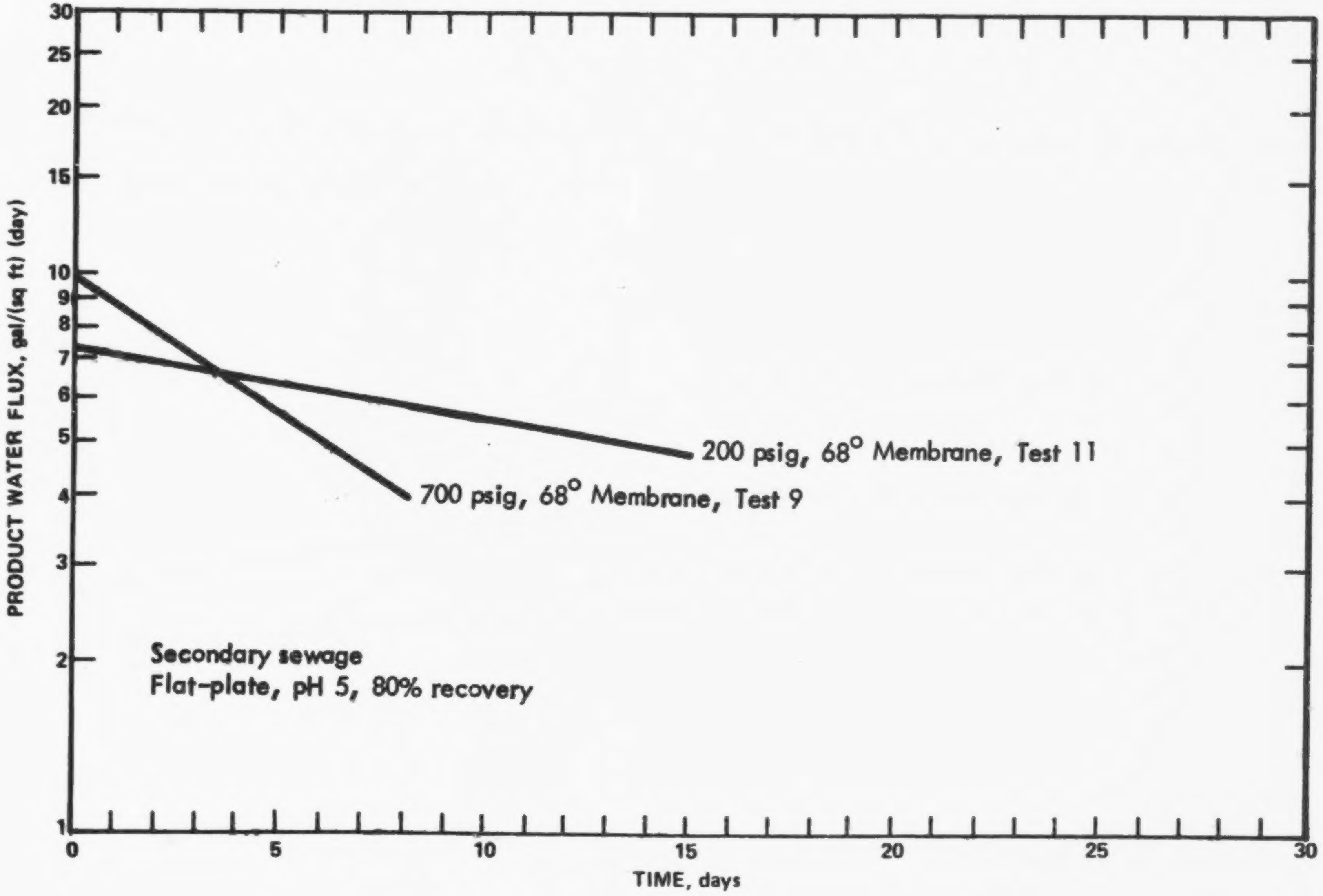

Figure 96. EFFECTS OF PRESSURE ON PRODUCT WATER FLUX DECLINE

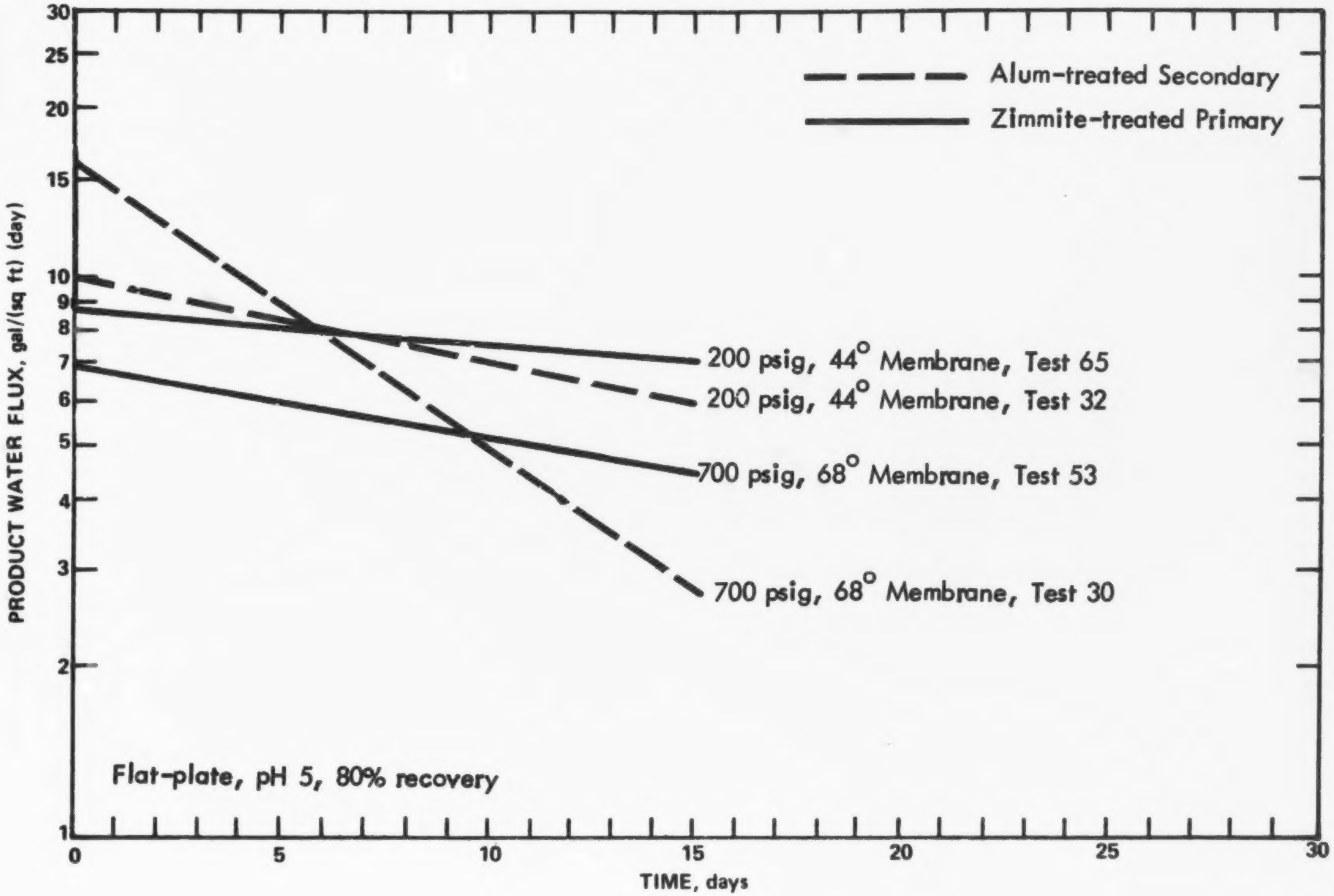

Figure 97. EFFECTS OF PRESSURE AND MEMBRANE PERMEABILITY ON PRODUCT WATER FLUX DECLINE

deposit on the membrane after a few hours of operation. The water, to reach the membrane surface, first must pass through the solids deposited on the membrane. A pressure gradient develops due to the pressure loss experienced by the water in penetrating the deposits and provides a force on the solids normal to the membrane surface counteracting the shear force of the bulk stream. At higher operating pressures, the layer of deposits becomes more compacted and provides a greater resistance to water flow and resultant higher pressure gradient across the deposits.

ADDITIVES

The use of additives to prevent product water flux decline was based on the premise that the solids deposited on or interacting with the membrane surface are a major factor in the decline and that certain additives could be helpful in preventing that deposition or interaction. In comparing the test results of various additives with carbon-treated sewage, shown in Figure 98, it appears that additives are detrimental to the performance. The control test had a slight decline in flux and greater total production of about 10 gal/(sq ft)(day) than with any additive. The test with Cyanamer developed a flux decline from 13 to 4 gal/(sq ft)(day) in 15 days. Close inspection reveals however that the tests with Zimmite 190 and Calgon produced negligible flux declines, although lower stabilized production levels of 6 and 7 gal/(sq ft)(day) were experienced. Since it is recognized that overdosing a sewage with polyelectrolytes can produce less than the desired result for any particular application; the dosages of additives were perhaps too high for this particular feed water.

Higher fluxes were obtained in the control tests performed with carbon-treated secondary sewage at the initiation of this study, which are believed due to both the uncontaminated nature of the apparatus and the exceptionally high quality of the feed water; but these results were disregarded in the foregoing analysis in favor of the results from the control tests obtained on the apparatus after it had undergone similar service to that for the additive tests.

In the treatment of secondary sewage with additive, the results of which are summarized in Figure 99, it was found that Zimmite 190 was best in preventing product water flux decline in the flat-plate test cells. The first test with Zimmite 190, Test 26, gave a positive product water flux decline slope at 80-percent recovery conditions; the usual initial drop in flux from the maximum capability of the membrane occurred prior to the 80-percent recovery level and thus prior to the value reported for the first day of operation. Nevertheless, this test with Zimmite 190 terminated at a higher flux than any of the other tests under similar conditions. A subsequent retrial (Test 84) of Test 26 resulted in a decline in product water flux from 14 to 9 gal/(sq ft)(day) in 15 days, terminating at the same level as the original test. Perhaps an undetermined slug of pollutant was responsible for the initial drop in Test 26 and the rest of the trial was the slow recovery brought on with Zimmite 190. The results from tests conducted with both no additive and Cyanamer indicated a lower stabilized flux of 6 gal/(sq ft)(day). Continuous addition of

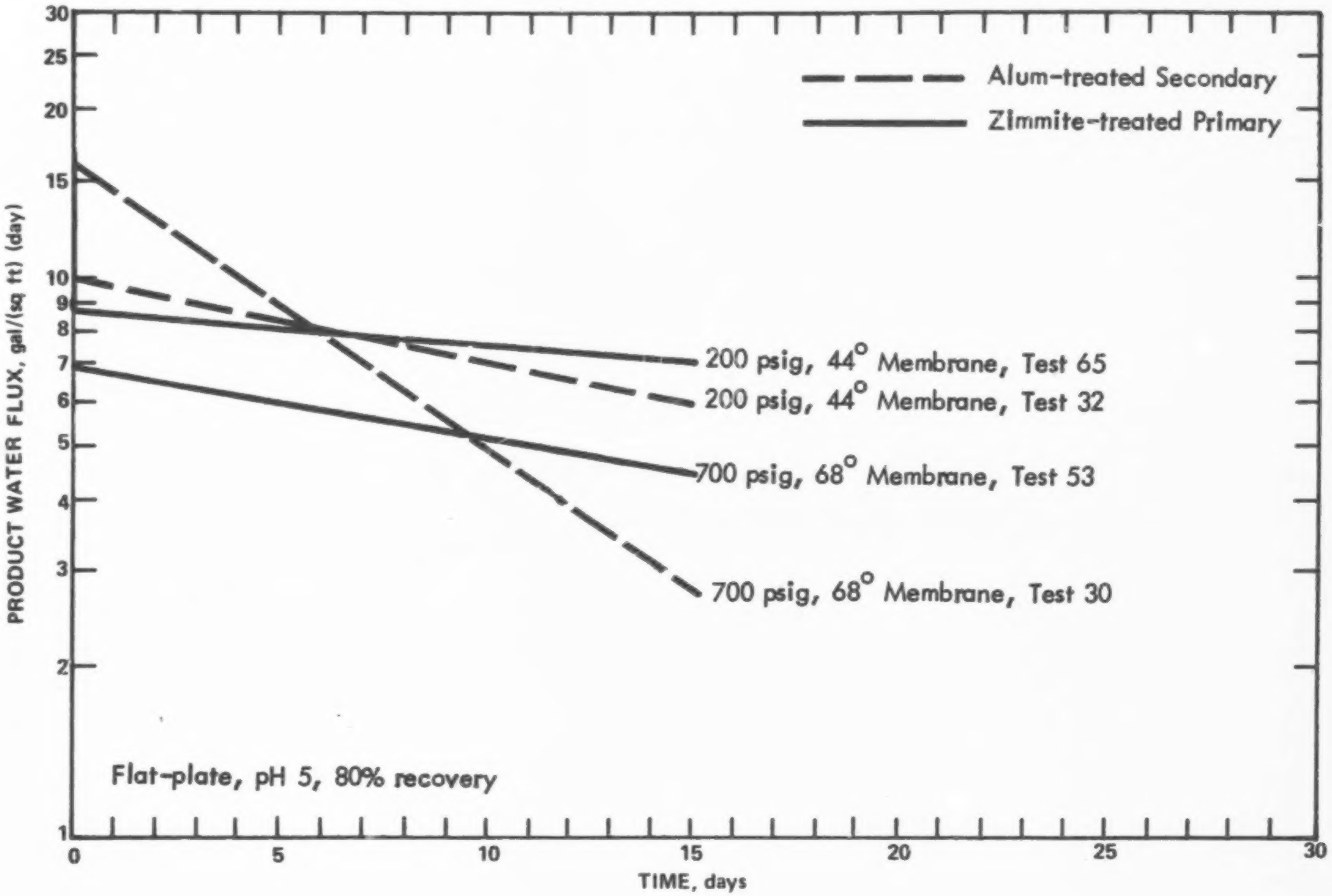

Figure 97. EFFECTS OF PRESSURE AND MEMBRANE PERMEABILITY ON PRODUCT WATER FLUX DECLINE

deposit on the membrane after a few hours of operation. The water, to reach the membrane surface, first must pass through the solids deposited on the membrane. A pressure gradient develops due to the pressure loss experienced by the water in penetrating the deposits and provides a force on the solids normal to the membrane surface counteracting the shear force of the bulk stream. At higher operating pressures, the layer of deposits becomes more compacted and provides a greater resistance to water flow and resultant higher pressure gradient across the deposits.

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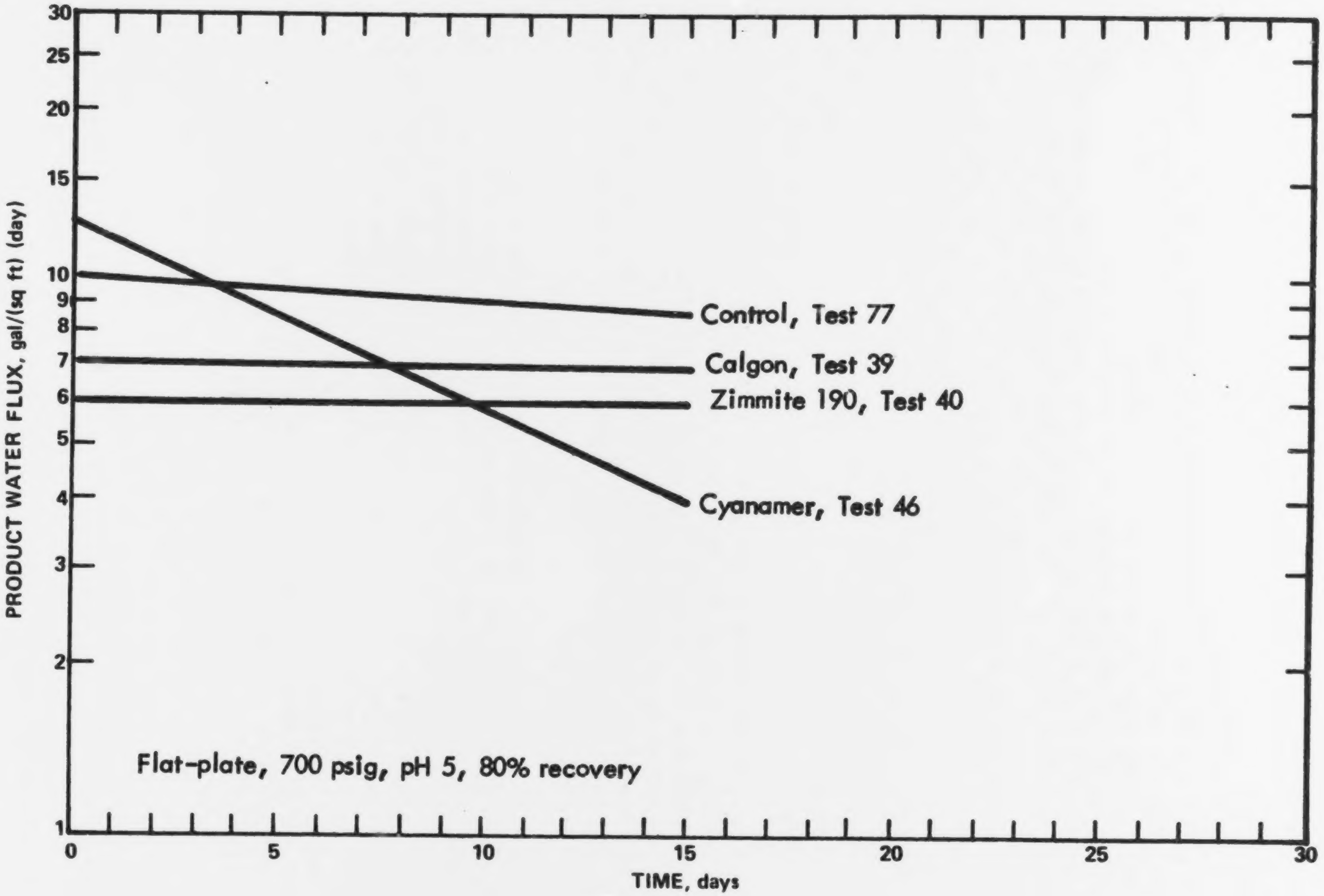


Figure 98. EFFECTS OF ADDITIVES WITH CARBON-TREATED SECONDARY SEWAGE

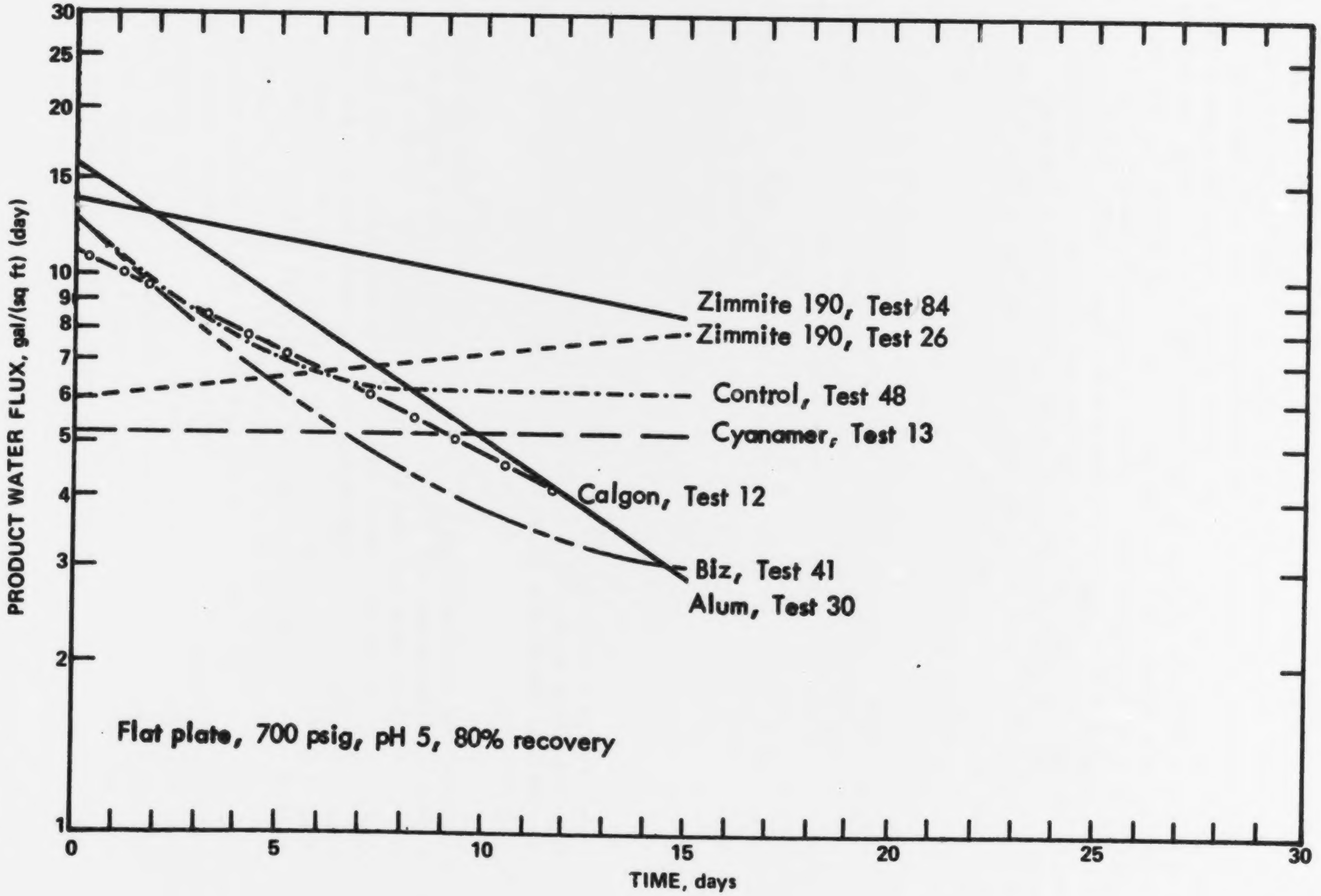


Figure 99. EFFECTS OF ADDITIVES WITH SECONDARY SEWAGE

Calgon and Biz appear to be of no value in preventing flux decline and possibly are detrimental as evidenced by production rates lower than that obtained with no additive.

Comparison of the results of alum-treated, sand-filtered secondary sewage in flat-plate test cells, presented in Figure 100, reveals significant initial flux declines in all tests from a high of approximately 15 gal/-(sq ft)(day) with ultimate stabilization of fluxes at less than 7 gal/(sq ft)-(day) for employed additives. The combination of alum treatment and dosage with Zimmite 190 provided a stable flux at 7 gal/(sq ft)(day) which was slightly better than with no additive whatsoever and substantially better than with Calgon, Cyanamer, or alum alone. It would appear that Zimmite 190 has a definite ability to reduce membrane fouling caused by calcium sulfate deposition, the presence of which was noted earlier in the discussion of test-cell geometry. The consistently superior performance of Zimmite 190 is again evidenced in Figure 101, which presents results of processing alum-treated secondary sewage in tubular membranes. The product water fluxes in all tests were quite high coupled with no product water flux decline after a small initial drop. Zimmite 190 in Test 35 achieved a stabilized flux of 16 gal/(sq ft)(day) which was slightly higher than observed with Cyanamer or no additive.

These test results indicate that an anionic flocculating agent without subsequent solids removal is more effective in the maintenance of higher fluxes than are a chelating agent or a dispersing agent in the concentrations utilized. Also the results clearly indicate the benefits derived from the use of a cationic flocculating agent (alum) with subsequent sand filtration. Pretreatment with alum achieved stable fluxes superior to those observed with the other additives alone. A test was performed with no removal of the alum floc (Test 70) to ascertain whether the effectiveness of alum treatment was associated simply with removal of solids or was the result of a conditioning or modification of feed water characteristics. A stable flux of 6 gal/(sq ft)(day) which was quite similar to those achieved with and without other additives was obtained in this test, indicating that the alum acts more to remove suspended and finely dispersed solids than to condition or modify the characteristics of the wastewater process stream.

A primary function of maintaining a fixed additive dosage with the various feed waters was to determine optimum additive dosage by varying the quality of the feed water and not the quantity of additive. Under the standard test conditions, primary, raw, and digester sewages, with their greater solids contents, were apparently too concentrated for the fixed additive dosages used and no improvements in flux were observed in either flat plates or tubes with continuous addition of Zimmite 190, Cyanamer, Zimmite 120, Calgon, or Biz. However, at a pH of 6 (standard test condition was pH of 5), the standard dosage of 2.2 mg/l of Zimmite 190 in primary sewage appeared adequate by providing a product water flux comparable to that obtained with alum-treated, sand-filtered primary sewage (cf. Figures 87 and 79). The dosages of additives used with secondary sewage, i.e., 10 mg/l for Cyanamer and 2.2 mg/l for Zimmite 190, apparently were adequate for that strength of sewage. The fixed dosage of Calgon

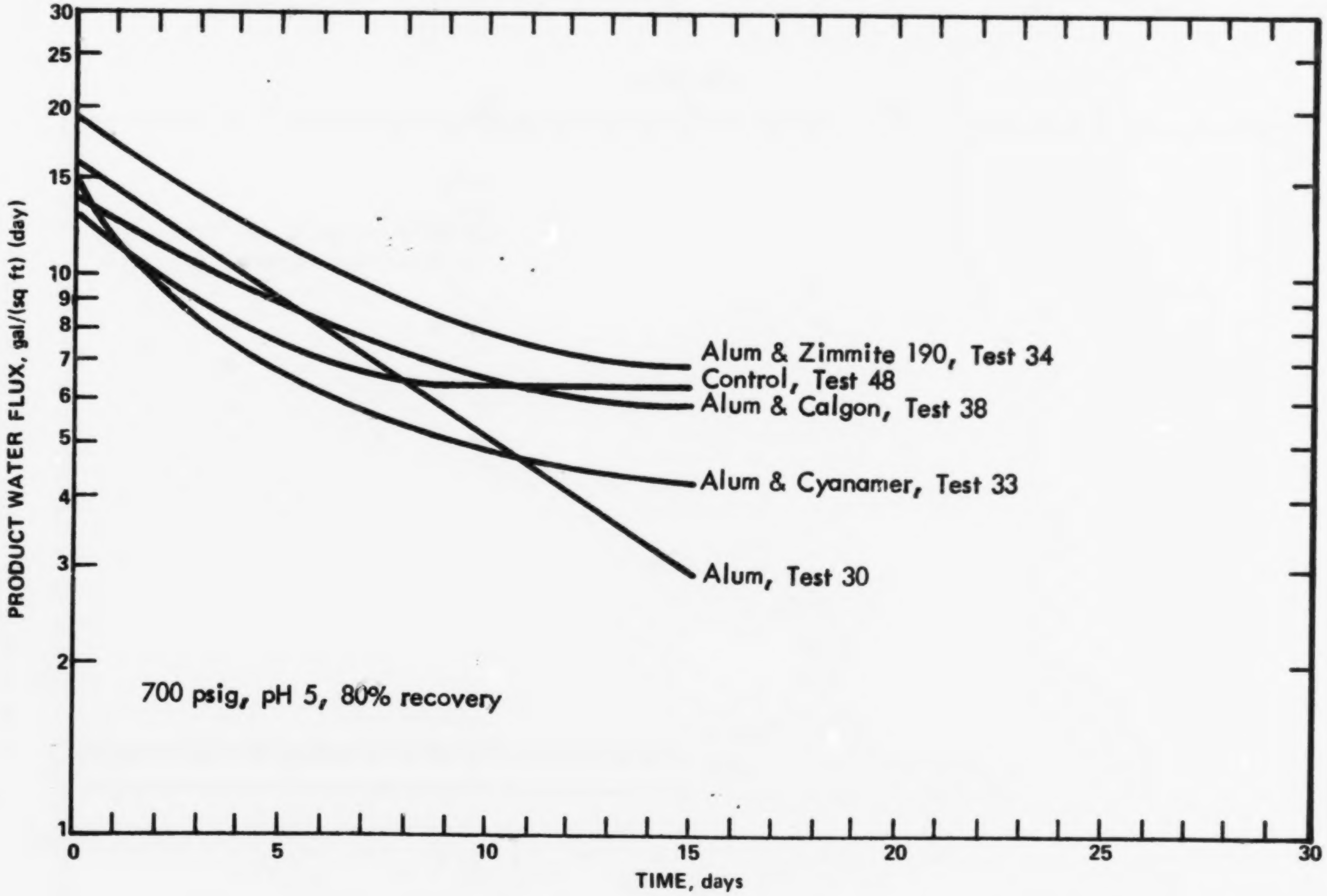


Figure 100. EFFECTS OF ALUM TREATMENT AND ADDITIVES WITH SECONDARY SEWAGE IN FLAT-PLATE TEST CELLS

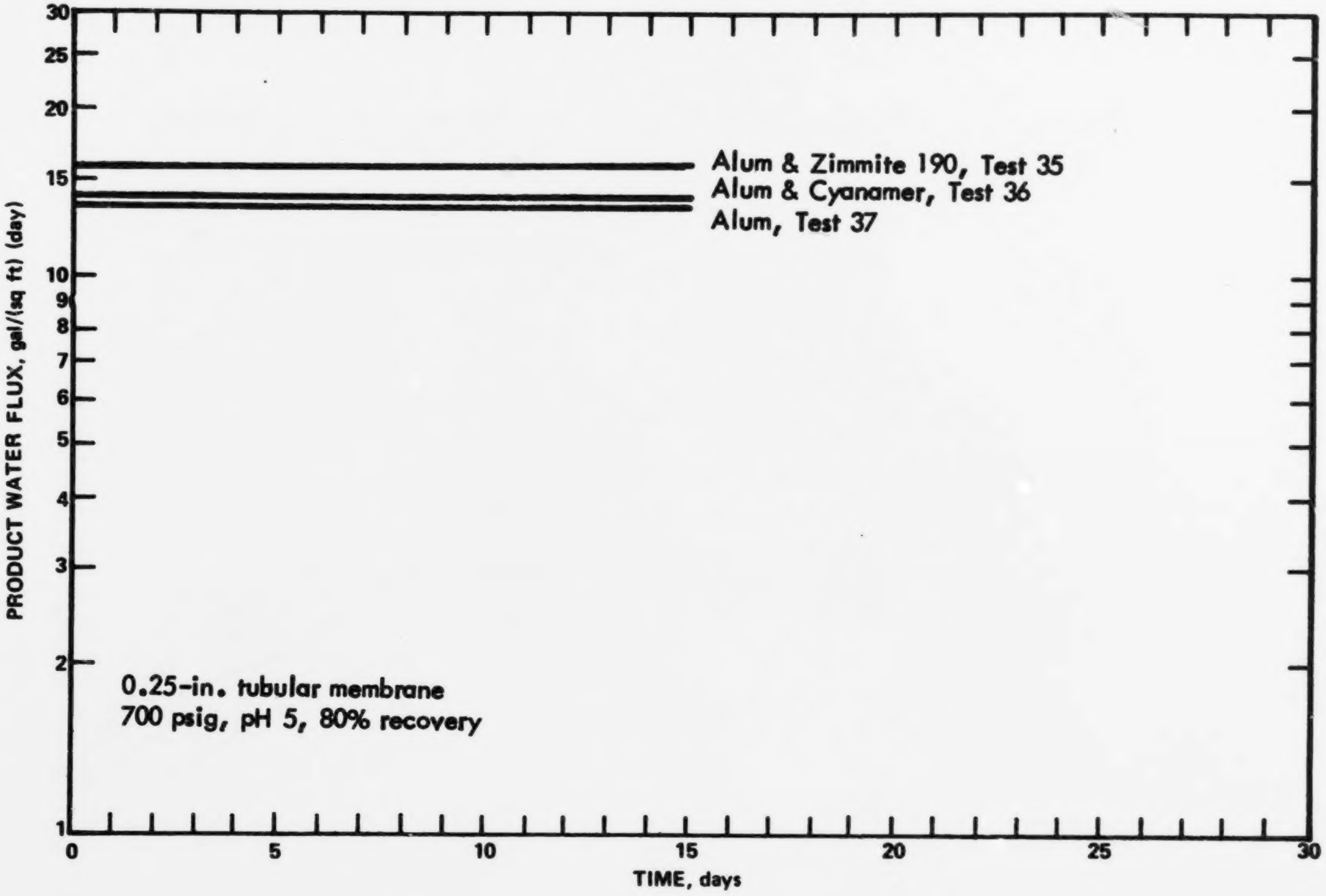


Figure 101. EFFECTS OF ALUM TREATMENT AND ADDITIVES WITH SECONDARY SEWAGE IN TUBULAR MEMBRANES

producing 10 mg/l concentrations was perhaps only effective with carbon-treated sewage.

To substantiate earlier results with alum treatment, a 0.56-in. diameter tubular membrane was tested with alum-treated, sand-filtered primary sewage. After 15 days operation, the flux decline became very small at 5 gal/(sq ft)(day) and the flux stabilized and never dropped thereafter below 4 gal/(sq ft)(day). After 60 days operation, when the recovery ratio had been increased to 95 percent, the product water flux increased to 5.5 gal/(sq ft)(day) for a total of 77-days operation. This performance was significantly better than the 2 to 3 gal/(sq ft)(day) flux obtained from 0.25-in. diameter tubular membranes with primary sewage and various additives other than alum.

Because of its generally superior performance with secondary sewage, Zimmite 190 was investigated further to determine the effects of pH and additive concentration on additive effectiveness. Primary sewage was selected for these tests to provide a reasonably high solids-bearing feed water. Figure 102 illustrates the results of testing one concentration (2.2 mg/l) of Zimmite 190 at various pH levels in flat-plate test cells. Similar flux declines were observed for all pH conditions, but the highest flux was achieved at a pH of 6, indicating that this pH was optimum for this additive and sewage combination.

The effects of different Zimmite 190 concentrations on product water flux with primary sewage are shown in Figure 103, which indicates for this wastewater and set of operating conditions that an optimum dosage of additive was obtained. A wastewater concentration of 2.2 mg/l of Zimmite 190 produced much higher product water fluxes than did a lower concentration of 1.1 mg/l, and also greater fluxes than were observed at the higher concentrations of 4.4, 6.6, and 8.8 mg/l. It appears therefore that Zimmite 190 concentrations of 4.4 mg/l and greater, although producing greater product water fluxes than little or no additive, were excessive in dosage, were less effective than smaller dosages, and produced on occasion more erratic results.

DEPRESSURIZATION

Standard test conditions included depressurization of the recirculating system at 8-hr intervals. This procedure resulted in small but noticeable increases in the product water flux usually on the order of 1 to 2 gal/(sq ft)(day) above the daily average which then declined to below average during the subsequent 8-hr period. All of the sudden increases in flux, such as shown in Figure 51, commenced from a depressurization event which therefore is an important catalyst in restoring product water flux.

RECOVERY RATIO

In Tests 76 and 86 (Figures 79 and 87, respectively) recovery ratios of 90 and 95 percent were achieved with primary sewage without degradation of the relatively stable product water flux. The stable fluxes associated with these recovery ratios indicate that within reasonable limits the recovery

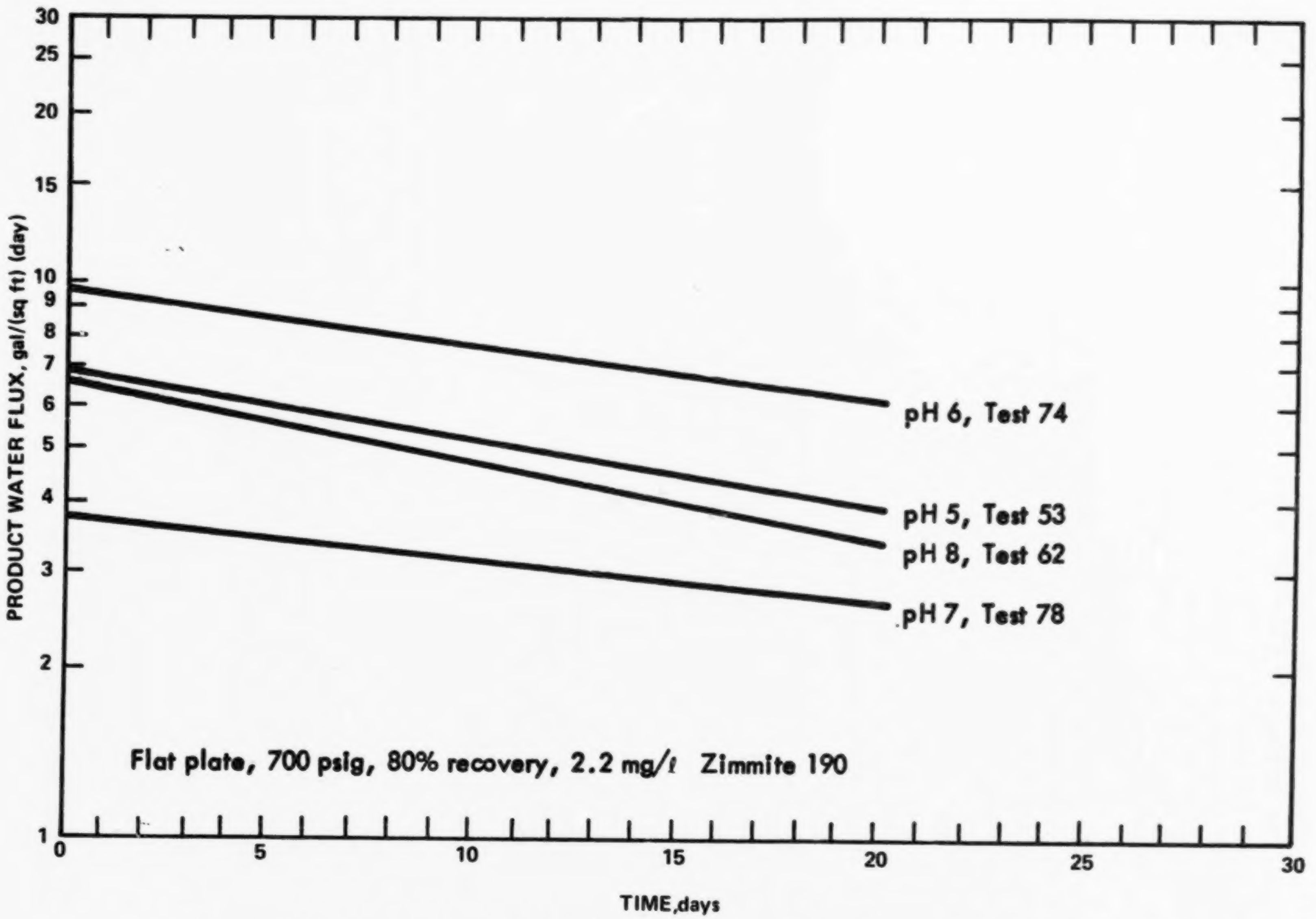


Figure 102. EFFECTS OF pH ON ZIMMITE 190 WITH PRIMARY SEWAGE

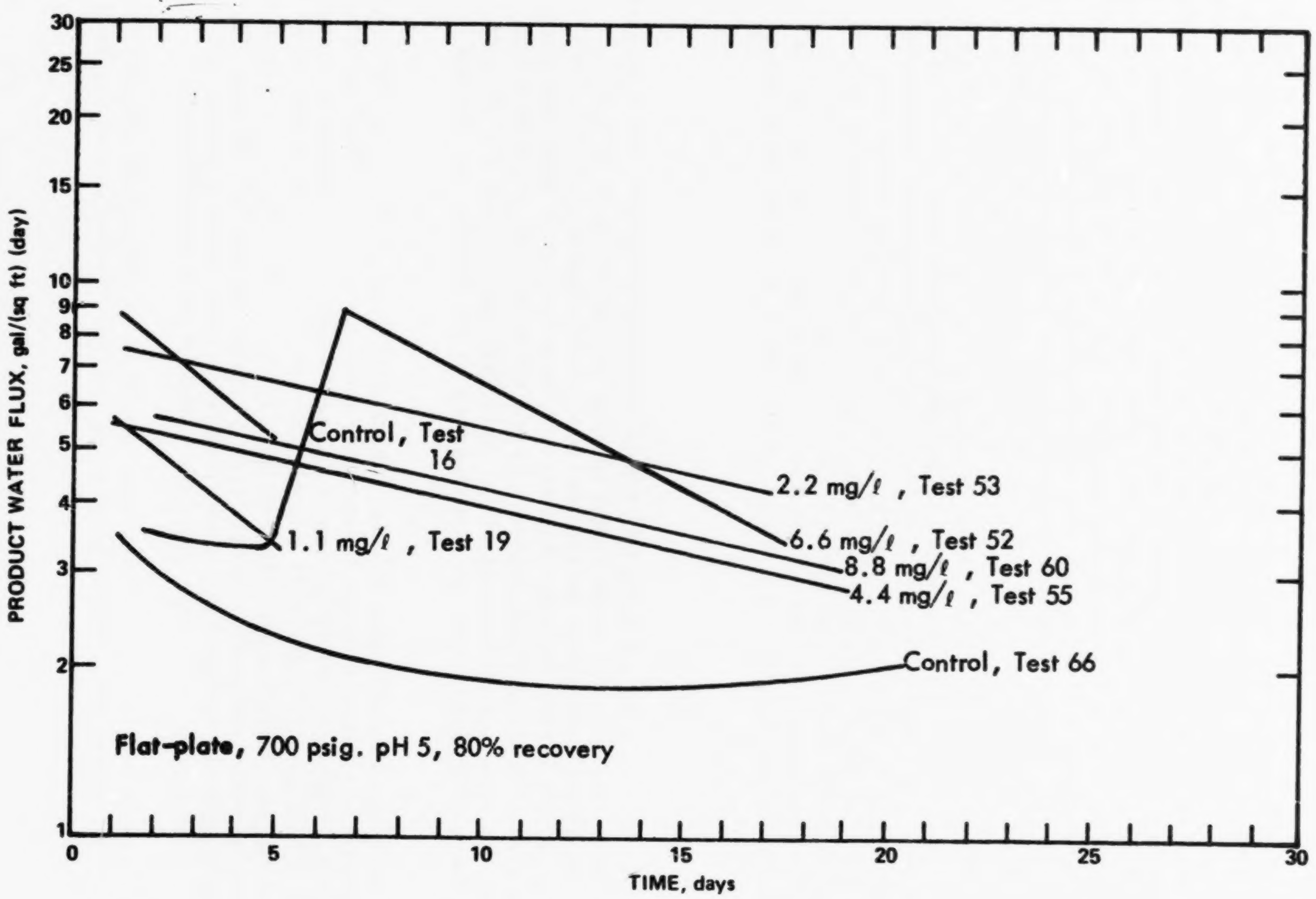


Figure 103. OPTIMIZATION OF ZIMMITE 190 DOSAGES FOR PRIMARY SEWAGE

ratio has little effect on product water flux. The rise in product water flux associated with operation at a 95-percent recovery ratio in Test 76 (Figure 79) and the lesser product water flux decline and flux variations observed at 90-percent recovery in Test 86 (Figure 87) in contrast to 80-percent recovery in Test 81 (Figure 86) hint at beneficial effects from unknown factors in the more highly concentrated feed water.

ADVANCED MEMBRANES

After the termination of the regular laboratory effort, newly developed tubular membranes of cellulose acetate-cellulose triacetate blend became available for testing. With an untrained skeleton crew and minimum supervision of the apparatus, alum-treated, sand-filtered primary sewage was again treated by reverse osmosis in the laboratory. The results of these tests are presented in Figures 104, 105, and 106, which indicate very high product water fluxes in the neighborhood of 15 to 18 gal/(sq ft)-(day) with strong signs of incipient flux stabilization at those levels. The advanced 0.56-in. diameter blend membranes had initial product water fluxes with brackish water of 30 gal/(sq ft)(day), at an operating pressure of 700 psig, or 29 μg/(sq cm)(sec)(atm). By comparison, the 0.56-in. diameter cellulose acetate membrane emplóyed during the regular test program, characterized by an initial flux with brackish water of 15 gal/-(sq ft)(day), at 700 psig pressure, or 15 μg/(sq cm)(sec)(atm), produced over the 77-day test duration (Test 76) an average product water flux of about 5.5 gal/(sq ft)(day) on alum-treated, sand-filtered primary sewage. Therefore it would seem that the level at which the product water flux stabilizes is highly dependent upon the inherent permeability of the membrane in addition to the feed water characteristics and other operating parameters.

THE FOULING MECHANISM

Of the many constituents contained in municipal wastewaters, the apparent participating species in the membrane fouling process can be broadly classified as gross settleable solids and particulate matter, finely dispersed solids, dissolved organic substances, and inorganic precipitates. Careful analysis of all accummulated results from this investigation has provided a qualitative assessment of the role that each of the aforementioned classes of foulants has in contributing to the membrane fouling process.

The effects of gross settleable solids, which are those materials removed by conventional primary sewage treatment, on the membrane fouling mechanism and the flux decline phenomenon appear negligible. Although there is a large difference in settleable solids concentrations between primary and raw sewages, tests conducted with both feed waters tended to stabilize at the same product water flux levels (cf. Figures 38 and 58, 50 and 59). Had gross settleable solids been contributary to membrane fouling, the final stabilized fluxes of the two sewages should have been different.

Finely dispersed, nonsettleable material appears to contribute greatly to the membrane fouling process by producing marked decreases in the level

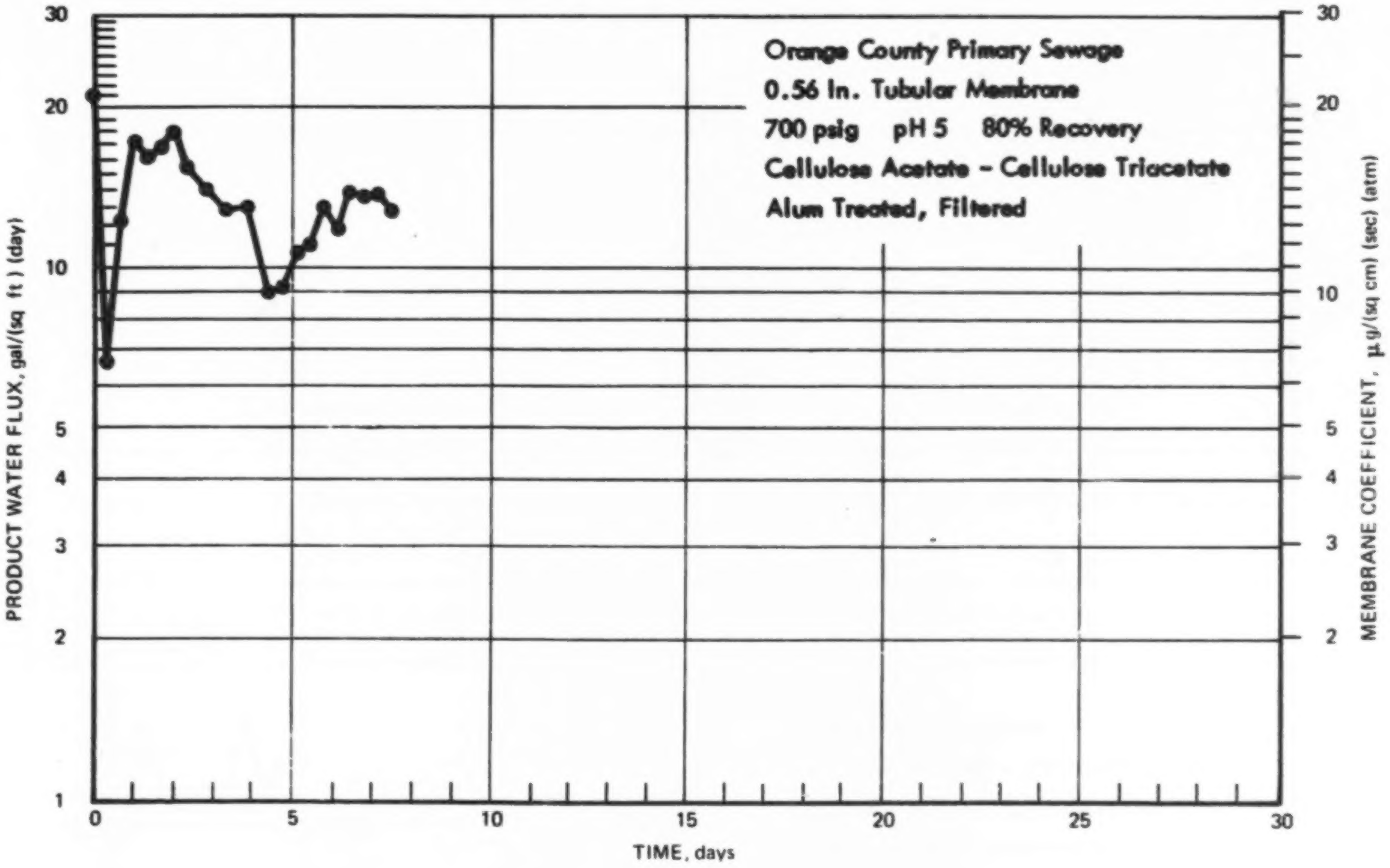


Figure 104. PRODUCT WATER FLUX, TEST 97

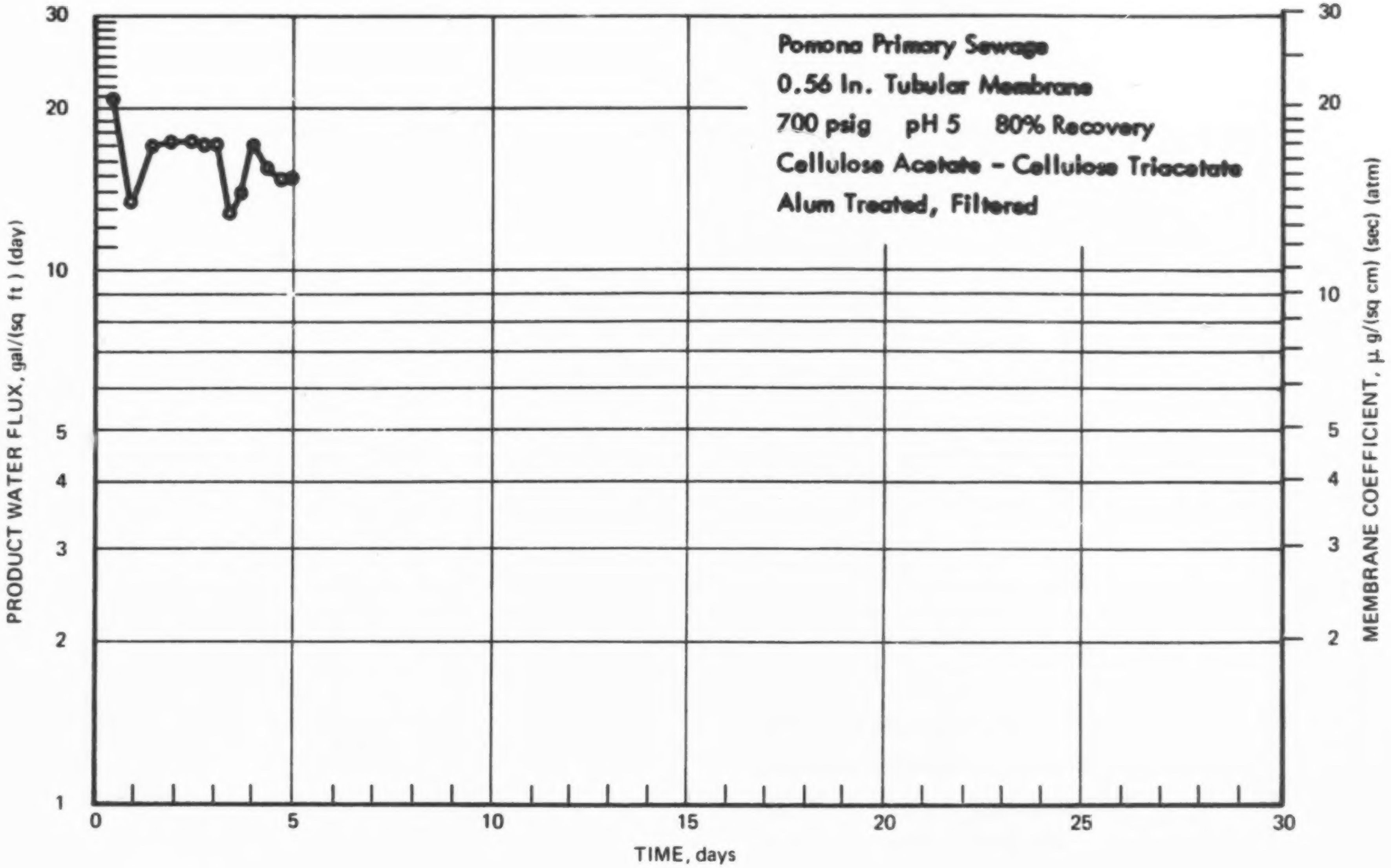


Figure 105. PRODUCT WATER FLUX, TEST 98

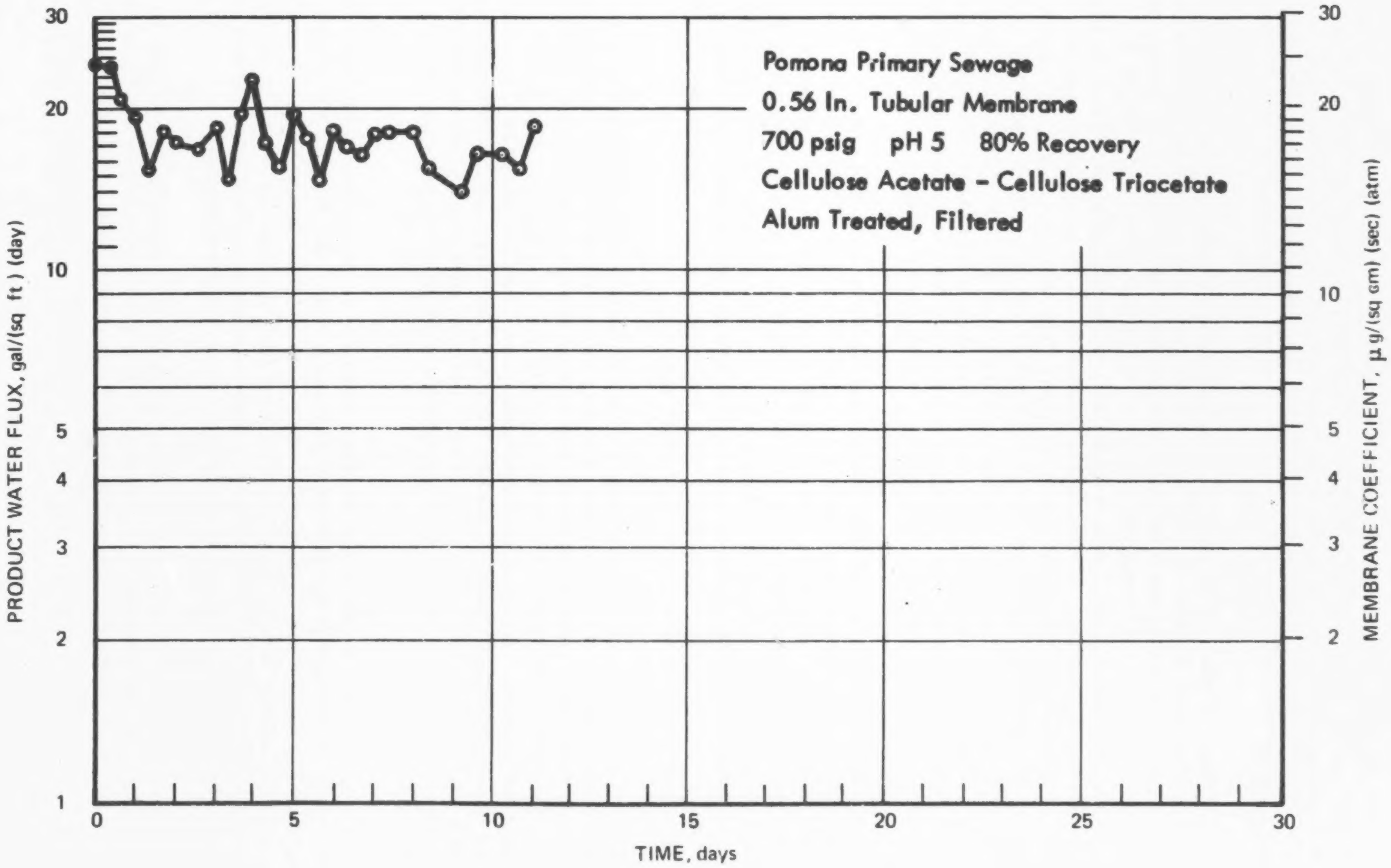


Figure 106. PRODUCT WATER FLUX, TEST 99

of stabilized product water fluxes. Tests conducted with alum-treated, sand-filtered secondary sewages processed in the tubular membranes produced at 700 psig relatively high product water fluxes of 15 gal/(sq ft)(day) with clarified wastewaters (cf. Figures 70 and 72). In the test with the unclarified alum-treated secondary sewage, visual inspection indicated that the flocculated solids were reconverted to the finely dispersed state by the rather severe agitation and turbulence created by the pump and other appurtenances in the wastewater recirculation system.

The contribution of dissolved organic substances to the overall reduction in product water flux levels would appear small in comparison to the nonsettleable solids. The most promising results obtained in this program were with primary and secondary sewages that had been subjected to alum treatment consisting of alum addition, flocculation, sedimentation, and sand filtration, which effects little removal of dissolved organic materials. At the beginning of the test program when the laboratory apparatus had not been exposed to wastewaters of any other quality, tests with carbon-treated secondary sewage, which contained practically no suspended solids and relatively low concentrations of finely dispersed solids and dissolved organics, produced product water fluxes equivalent in terms of ultimate membrane capability to those obtained with alum-treated, sand-filtered secondary sewage. Subsequent tests with carbon-treated secondary sewage produced notably lower product water fluxes, which is attributed partially to visible residual materials in the system from earlier tests with lower grades of municipal wastewater and to undetected differences in feed water quality. Although no significant differences could be noted between the compositions of the carbon-treated secondary sewages collected at the different times of the year, the second set of reverse osmosis tests were conducted just prior to and during regeneration of the carbon columns.

Under the proper hydraulic conditions, in addition perhaps to the availability of minute amounts of solids, the presence of ions in municipal wastewaters that may precipitate on the membrane surface does not appear to present a critical factor in membrane fouling and reduced product water fluxes. Near the termination of Test 76 (Figure 79), which employed alum-treated, sand-filtered primary sewage and a tubular membrane, the system was purposely supersaturated with calcium sulfate and operated for four days without the occurrence of measurable product water flux decreases.

In general, an initial product water flux decline is observed when processing municipal wastewater by reverse osmosis that, depending upon the wastewater characteristics, extends over a period of from several days to several weeks, after which time no further flux decline is evident and a stabilized product water flux occurs. A phenomenological membrane fouling model is postulated that accounts for these observations.

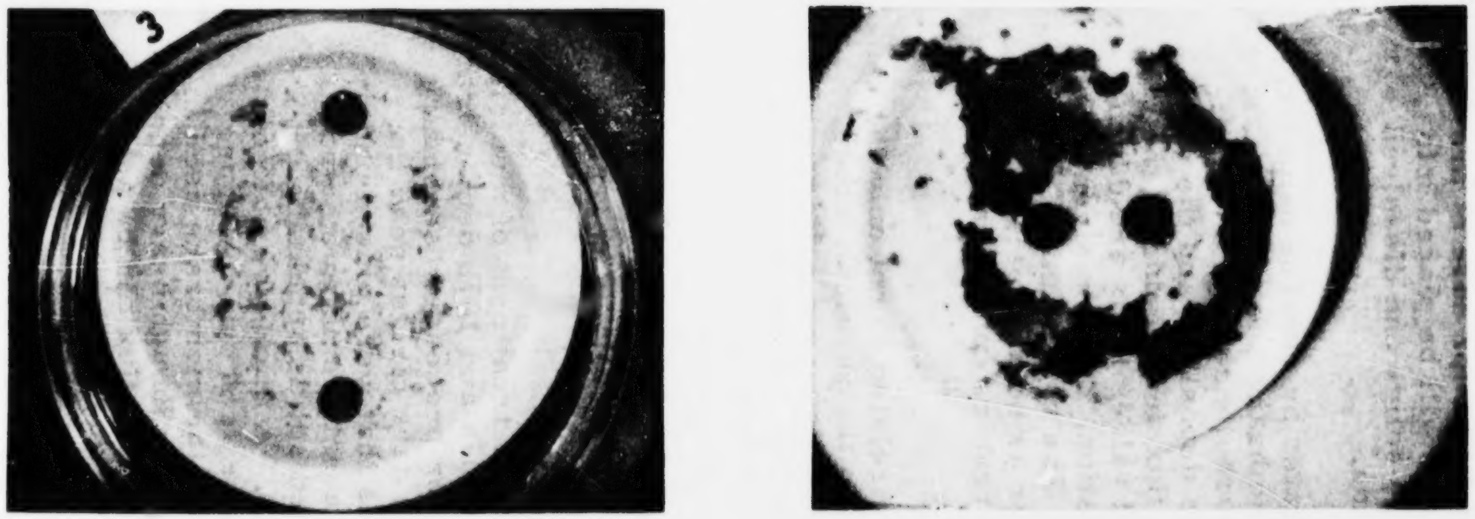
The effect of intrinsic compaction of the membrane during operation is ignored in this model because the relative product water flux decline associated therewith is negligible, particularly over the real time considered herein. Both the membrane characteristics and the operating pressure are considered to be the same for all feed water conditions.

For purposes of developing the postulated model and for ease of presentation, the principal membrane fouling agents will be placed into two categories--finely dispersed, nonsettleable solids and dissolved organics that produce cohesiveness of the solids.

At the outset of processing a solids-bearing water by reverse osmosis, the solids deposit on the extremely smooth membrane surface increasing the surface roughness and concomitant local turbulence until an equilibrium is established between the rate of solids deposition and the rate of solids removal. Both the magnitude of the flux decline during the initial deposition and the subsequent stabilized value of flux are dependent upon the finely dispersed solids concentration, the cohesiveness of the deposited solids and the local turbulence. The rate of initial flux decline is greater and the stabilized flux lesser as both dispersed solids concentration and cohesiveness or dissolved organics concentration increase.

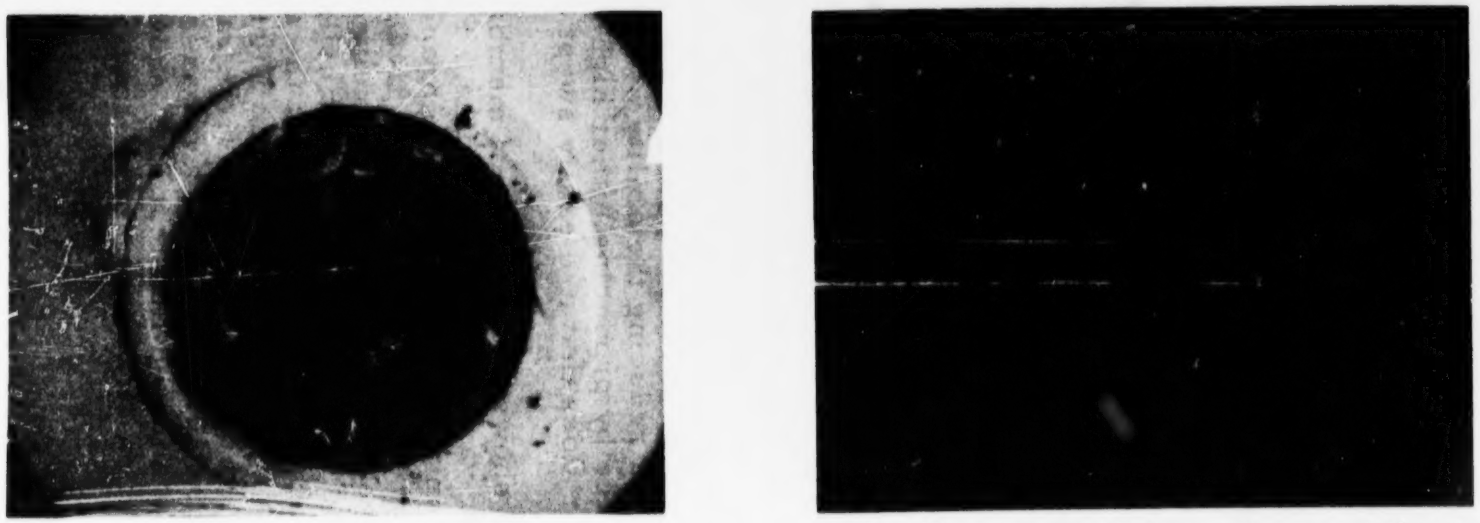
The degree of deposited solids cohesiveness is related to not only the concentration of dissolved organic substances but to the physical, other chemical, and electrical properties of the finely dispersed solids, which determine the agglomerative tendency and capacity to form larger and more dense, less permeable deposits. Thus the presence of strongly charged polyelectrolytes can significantly alter the properties of the dispersed solids by both counteracting the adhesive capacity of the organic materials and reducing the ability of the solids to intensify on the membrane surface by producing either highly repellant similarly charged particles or flocs that are easily swept along.

Figure 107 shows photographs of membranes after treatment of municipal sewages for varying periods of time. Figures 107a and 107b demonstrate the change in appearance of a membrane used for processing secondary sewage after 6 and 18 days, respectively. The dark circles near the center of the membrane are reinforcing patches that were placed under the inlet and outlet ports of the test cells to prevent membrane damage and have shifted position. Some of the deposited solids appearing in Figure 107a have been displaced in Figure 107b. A thick layer of solids was deposited on the membrane from raw sewage as shown in Figure 107c. Figure 107d, depicting a cross-section of the membrane used in the 77-day stabilized flux test run, shows that even though heavy deposits are apparent on the membrane a steady, appreciable flux can be achieved.



a. Secondary Sewage, Test 13
6-days operation

b. Secondary Sewage, Test 13
18-days operation



c. Raw Sewage, Test 20
10-days operation

d. Alum-treated Primary Sewage, Test 76
77-days operation

Figure 107. PHOTOGRAPHS OF REVERSE OSMOSIS MEMBRANES AFTER PROCESSING OF MUNICIPAL WASTEWATER

Section VI

REVERSE OSMOSIS PROCESS MODEL

A mathematical model of the reverse osmosis process to determine performance and costs from influent wastewater characteristics and specified operating conditions and equipment features has been prepared for use as a subroutine in the Federal Water Quality Administration's "Digital Computer Program for Preliminary Design of Wastewater Treatment Systems."

The reverse osmosis system is based on a plant in the capacity range of from 1 to 100 mgd containing tubular membrane units, placed in parallel-flow configuration, that decrease in number downstream or as the wastewater proceeds through the process. In addition to influent wastewater quality and quantity supplied by the executive pro gram from the immediately upstream process, the operational parameters that must be specified are:

Overall plant product water recovery ratio, i. e., the ratio of product water flow rate to feed water flow rate.

Maximum total operating pressure of plant.

Membrane coefficient applicable to wastewater feed quality.

Excess plant capacity factor.

The preliminary plant design is based on the following conditions or assumptions:

The wastewater velocities, hence Reynolds numbers, are constant throughout the plant.

The osmotic pressure is determined from the total dissolved solids concentration and not from the summation of individual ionic species.

The total average product water flux of the plant is based on an average effective pressure obtaining through the length of the plant, i. e., average effective pressure is the total operating pressure less both the average osmotic pressure and the average frictional head loss.

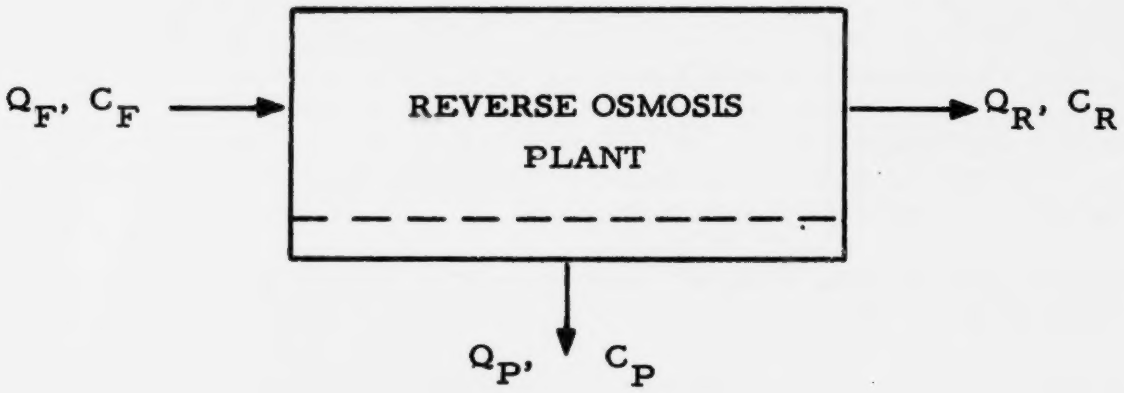
The permeation or rejection of individual species is constant throughout the plant and is a function only of the membrane character.

The adjustment of wastewater pH by acid addition is considered an external pretreatment process and is not included in the reverse osmosis model particularly since it may not be necessary to the successful operation of the reverse osmosis process.

Energy is recovered from the waste stream by means of a turbine.

PROCESS MODEL DEVELOPMENT

A basic flow sheet for the reverse osmosis process or plant is shown in the accompanying sketch,



where Q_F, Q_P, and Q_R represent stream volumes or flow rates of the feed water, the purified product water, and the reject wastewater, respectively; and C_F, C_P, and C_R signify the corresponding concentrations of a wastewater constituent or solute in the process streams.

As the feed water progresses through the plant, the solute concentration on the wastewater side of the membrane increases continuously due to a much higher transport rate of water through the membrane than of solute. Both the water and solute fluxes in the membrane vary to some extent in the plant due primarily to the presence of nonuniform flow conditions, but for the purposes of this development they are assumed to be constant throughout the plant for any given set of operating conditions and plant configuration.

The solute flux through the membrane is expressed conveniently as a permeation or rejection, defined as

$$p = 1-r = C_P/\bar{C} \tag{1}$$

where p and r are solute permeation and solute rejection by the membrane, respectively, and $\bar{C}$ is the average bulk solute concentration in the wastewater throughout the entire process or plant.

The product water recovery ratio, R, which is the ratio of feed water flow into a section of the process to the product water flow from that section, increases from zero at the inlet of the plant to a maximum value which is the overall recovery ratio for the complete plant, defined as

$$R = Q_P / Q_F \tag{2}$$

From the materials balance on the water and the solute, respectively,

$$Q_F = Q_P + Q_R \tag{3}$$

and

$$Q_F C_F = Q_P C_P + Q_R C_R \tag{4}$$

and the substitution of the product water recovery ratio parameter, the inter-relation between the solute concentrations in the process streams in terms of the product water recovery ratio becomes

$$C_R = (C_F - RC_P)/(1-R) \tag{5}$$

The concentration of solute in the product water from a section, designated by the primed values, is

$$C'_P = \frac{1}{R'} \int_0^{R'} (1-r)\bar{C}' \, dR' \tag{6}$$

where R' is the section recovery ratio and $\bar{C}'$ is the concentration of solute on the wastewater side of the membrane.

Substitution of Equation 6 into Equation 5, applied to a section with recovery R', provides an integral equation in $\bar{C}'$, namely

$$C' = \frac{1}{(1-R')} \left[C_F - \int_0^{R'} (1-r) \, \bar{C}' \, dR' \right] \tag{7}$$

Differentiation of Equation 7 with respect to R' gives

$$d\bar{C}' / \bar{C}' = r \, dR' / (1-R') \tag{8}$$

which upon integration between the limits of 0 and R' and C_F and $\bar{C}'$ provides the concentration of solute on the wastewater side of the membrane at the end of the section with recovery R', namely

$$\bar{C}' = C_F (1-R')^{-r} \quad (9)$$

The solute concentration of the discharge from the plant is

$$C_R = C_F (1-R)^{-r} \quad (10)$$

The overall plant average solute concentration on the wastewater side of the membrane is obtained from the integration of Equation 9 between the recovery ratio limits, or

$$\bar{C} = \frac{1}{R}\int_0^R C_F (1-R')^{-r}\, dR' \quad (11)$$

The solutions to Equation 11 are

$$\bar{C} = \frac{C_F \left[1-(1-R)^{1-r}\right]}{R(1-r)} \qquad \text{when } r \neq 1 \quad (12)$$

and $$\bar{C} = \frac{-C_F \ln(1-R)}{R} \qquad \text{when } r = 1 \quad (13)$$

The solute concentration in the overall plant product water as a function of feed water solute concentration is found by substitution of Equation 10 into Equation 5,

$$C_p = \frac{C_F}{R} \left[1-(1-R)^{1-r}\right] \quad (14)$$

The production of purified water from the reverse osmosis process is determined from the product of the membrane surface available and the product water flux associated with the membrane and other operating conditions. Therefore the plant size required to provide a specified production capacity is determined by the particular membrane characteristics.

Product water flux is a function of the intrinsic water transport properties of the membrane, the nature of the feed wastewater, and the applied pressure on the wastewater side of the membrane. The intrinsic rate at which water permeates through the membrane is described by the intrinsic membrane coefficient and is dependent upon the membrane formulation, casting procedure, and annealing conditions. The membrane coefficient for a particular application is measured in a test facility under the same hydraulic conditions and pressure that would be experienced in the plant and with the wastewater to be processed. Thus the effects of both the feed water quality and the greater than bulk solute concentration that obtains at the membrane surface are incorporated into the membrane coefficient and can be disregarded from further consideration.

The product water flux can be expressed by combining the membrane flux coefficient and the operating pressure, or

$$J = 1.45 \times 10^{-3} A_o P \qquad (15)$$

where J is expressed in gal/(sq ft)(day), A_o is expressed in μg/(sq cm)(sec)(atm), and P is expressed in psig.

The effective pressure responsible for the transport of water through the membrane is a function primarily of the total operating or plant inlet pressure reduced by the osmotic pressure exerted by the solutes in the wastewater and the frictional losses encountered in the reverse osmosis tubes and fittings. For the overall process or plant, the average effective pressure can be approximated by

$$\bar{P} = P_F - \bar{P}_O - \bar{P}_L \qquad (16)$$

where $\bar{P}$ is the plant average effective pressure, P_F is the maximum operating pressure obtaining at the plant inlet, $\bar{P}_O$ is the average osmotic pressure occurring throughout the plant, and $\bar{P}_L$ is the average pressure drop experienced across the plant due to frictional losses.

Osmotic pressure of a dilute solution is a function of the total solute concentration, or simply

$$P_O = k_1 RTC_S = k_2 C_S \qquad (17)$$

where P_O is the osmotic pressure, k_1 and k_2 are proportionality constants, R is the universal gas constant, T is the absolute temperature, and C_S is the solute concentration. In dilute solutions k_1 is very nearly unity, but in more concentrated solutions it becomes quite dependent upon the type and only slightly dependent upon the concentration of solute, as shown in Table 7. Because the concentration of individual solute species is usually unknown and variable with time and source, the osmotic pressure of municipal wastewater can be determined sufficiently accurately from the total dissolved solids content. If the values presented in Table 7 for $CaCl_2$ are taken as being typical of municipal wastewater in its many states, the osmotic pressure constant, k_2, at 25° C becomes 0.00866 psig/ppm. By comparison,

Table 7

OSMOTIC PRESSURES OF PURE SOLUTIONS
(psi at 25°C)

Concentration ppm	NaCl	Na_2SO_4	$CaCl_2$	$MgSO_4$	$MgCl_2$
500	5.65	2.67	4.33	1.90	5.36
10,000	113	53.4	86.8	38.0	107
50,000	565	267	433	190	536

sea water with a total dissolved solids concentration of 34,500 ppm exerts an osmotic pressure of 25.1 atm at 25°C, which results in a constant, k_2, equal to 0.0107 psig/ppm. In this development, a value of $k_2 = 0.010$ psig/(mg/l) of total dissolved solids will be used to include the increased concentration occurring at the membrane surface due to boundary layer conditions. Thus the osmotic pressures associated with the feed water to and the reject wastewater from the reverse osmosis process can be related to the total dissolved solids content of the feed water by the expressions, respectively,

$$P_{OF} = 0.010 \ TDS_F \qquad (18)$$

and

$$P_{OR} = 0.010(1-R)^{-r} \ TDS_F \qquad (19)$$

where P_{OF} and P_{OR} are osmotic pressures in psig of feed and reject wastewaters, respectively, and TDS_F is total dissolved solids concentration in feed water as mg/l. The average osmotic pressure on the wastewater side of the reverse osmosis membrane can be calculated from Equation 12 in terms of feed water total dissolved solids concentration, and becomes

$$\bar{P}_O = \left\{\frac{0.010\left[1-(1-R)^{1-r}\right]}{R(1-r)}\right\} TDS_F \qquad \text{for } r \neq 1 \qquad (20)$$

The total head or pressure loss through the plant is a function of total series tube length, tube diameter and roughness, number and type of flow constrictions and disturbances, and the velocity or quantity of flow through the plant. Because water is removed from the wastewater stream as it progresses through the process, and because it is necessary to maintain the wastewater stream at a turbulent condition above some minimum, the cross-sectional area of the reverse osmosis plant must decrease downstream if recirculation of reject wastewater is not practiced. In the plants of large capacities considered for this development, i. e., 1 to 100 mgd, it is possible to provide, for all practical design purposes, identical flow conditions in all flow channels or tubes. This feature of constant Reynolds number and constant individual tube velocity simplifies the plant design to a single tapered configuration which is believed most applicable for the intended use of this reverse osmosis model.

Total plant head loss can be estimated from the relation

$$P_L = k_3 L_s v_t^2/d \tag{21}$$

where P_L is overall pressure drop in the plant due to frictional losses, k_3 is the constant of proportionality, L_s is the total tube length for series flow, v_t is the cross-sectional flow velocity in a tube, and d is the tube diameter. For a reverse osmosis plant possessing a constant Reynolds number throughout, the total length of tubes in series-flow configuration is

$$L_s = \frac{k_4 a_t v_t}{\bar{J} s} = \frac{k_4 \pi d^2 v_t}{4 \bar{J} \pi d} = \frac{k_4 d v_t}{4 \bar{J}} \tag{22}$$

where k_4 is the unit conversion factor, a_t is the cross-sectional area of the tube, $\bar{J}$ is the average product water flux, and s is the specific membrane surface area. Replacing the velocity term in Equations 21 and 22 with the appropriate Reynolds number, $N_R = v_t d/\nu$, and substituting Equation 22 into Equation 21, the head loss is

$$P_L = k_3 k_4 \nu^3 N_R^3 / (4 \bar{J} d^3) \tag{23}$$

where ν is kinematic viscosity of the wastewater. The average frictional pressure loss for this flow configuration is simply

$$\bar{P}_L = P_L /2 \tag{24}$$

Collecting terms into a single constant of proportionality, the expression for average head loss through the reverse osmosis plant as a function of design and operating parameters reduces to

$$\bar{P}_L = k_5 N_R^3/(\bar{J} d^3) \tag{25}$$

where $$k_5 = k_3 k_4 \nu^3/8 = k_6 \rho f \nu^3/(16\ g_c) \qquad (26)$$

and k_6 is a factor incorporating frictional losses due to bends, valves, contractions, and expansions in the flow channels and is assumed to equal 2, i. e., these losses are equal to the frictional losses resulting from flow in straight tube lengths (45 ft in the Aerojet-General modules); ν is evaluated at 60° F and equal to 1.2×10^{-5} (sq ft)/sec; ρ is the density of the wastewater and taken as 62.4 lb_m/(cu ft); f is the friction factor which is assumed constant in this development for simplicity and equal to 0.031, a value representing a smooth pipe at a Reynolds number of 10,000; and g_c is the gravitational constant equal to 32.2 (lb_m)-(ft)/(lb_f)(sq sec). Evaluation of k_5 and insertion into Equation 25 produces

$$\bar{P}_L = 5.82\text{x}10^{-14}\ N_R{}^3 / (\bar{J} d^3) \qquad (27)$$

where $\bar{P}_L$ is expressed in psig, $\bar{J}$ in gal/(sq ft)(day), and d in ft. The commercially available reverse osmosis tube internal diameters are limited to sizes ranging from about 0.4 to 0.6 in. To reduce the opportunity for misuse of the computer program by the input of unrealistic diameters and Reynolds numbers and to provide a diameter compatible with the cost expressions incorporated, a value of 0.56 in., corresponding to the Aerojet-General internal tube diameter, and a Reynolds number of 10,000 are substituted into Equation 27 resulting in

$$\bar{P}_L = 573/\bar{J} \qquad (28)$$

The relations between average product water flux and the known operating parameters can be summarized by appropriate substitution of Equations 15, 20, and 28 into Equation 16, namely

$$\frac{\bar{J}}{1.45\text{x}10^{-3} A_o} = P_F - \left\{ \frac{0.010\ [1-(1-R)^{1-r}]}{R(1-r)} \right\} TDS_F - \frac{573}{\bar{J}} \qquad (29)$$

The appropriate root from the solution of Equation 29 is

$$\bar{J} = \frac{B + (B^2 - 4AC)^{0.5}}{2A} \qquad (30)$$

where
$$A = 1/(1.45\times10^{-3} A_o) \tag{31}$$

$$B = P_F - \left\{\frac{0.010\,[1-(1-R)^{1-r}]}{R(1-r)}\right\} TDS_F \quad \text{for } r \neq 1 \tag{32}$$

$$C = 573 \tag{33}$$

The total surface area requirement for the reverse osmosis plant can be determined according to the relation

$$S = Q_P \times 10^6 / \bar{J} = RQ_F \times 10^6 / \bar{J} \tag{34}$$

where S is expressed in sq ft, Q_P and Q_F in mgd, and J in gal/(sq ft)(day). This expression can be converted to the total length of all tubes contained in the plant by applying the specific membrane surface area,

$$L_T = S/s \tag{35}$$

where L_T is given in ft and s is equal to 0.147 (sq ft)/ft for the 0.56-in. diameter tube.

The power consumed to operate the reverse osmosis plant with a pumping efficiency of 0.8 is

$$KW = 0.379\, Q_F P_F \tag{36}$$

where KW is expressed in kw, Q_F in mgd, and P_F in psig. The power recoverable with a turbine of 0.7 efficiency placed at the outlet of the reverse osmosis plant can be calculated as follows,

$$KW_T = 0.212\, Q_W (P_F - P_L) = 0.212(1-R)\, Q_F (P_F - P_L) \tag{37}$$

Therefore the net power requirement is

$$KW_N = Q_F \left[0.379\, P_F - 0.212(1-R)(P_F - P_L)\right] \tag{38}$$

PROCESS COST DEVELOPMENT

Major capital cost elements for a reverse osmosis plant consist of support structures for the membraned tubes, fittings and valves, high-pressure pump, turbine generator for energy recovery, instrumentation, power substation, and site improvements and housing. Membraned tubes are not included in the construction cost since they are disposable after their useful life, which is assumed to be two years in this development; hence tube cost is included as an annual operating expense.

Costs used in this model are based on the modular design of the Aerojet-General reverse osmosis system, which contains 11,520 lineal ft equivalent to 1,700 sq ft of membrane surface area. The modules are self-supporting and contain all necessary connections between individual tubes, which can easily be placed either in series or parallel configuration, all valves and fittings, and product water collectors. The estimated cost in dollars of the total number of required modules without membraned tubes as a function of total plant membrane surface area is

$$\mathrm{CMODU} = 2.65S \tag{39}$$

Capital costs of items common to the modules are dependent upon plant capacity and other operating parameters and are based on suppliers quotations and estimates for equipment associated with plants of several different sizes in the 1- to 100-mgd range. A scaling exponent of 0.7 is employed on those parameters where economy of scale can be realized.

The estimated capital costs in dollars for high-pressure pumps are based on the use of a minimum of three separate pumps and can be determined from

$$\mathrm{CPUMP} = 224\,(Q_F\, P_F)^{0.7} \tag{40}$$

In these applications a turbine-generator for the recovery of flow energy from the reject stream can be considered as simply a motor pump running backwards at a lesser efficiency, and thus its capital cost in dollars can be estimated from

$$\mathrm{CTURB} = 224\left[(1-R)Q_F\,(P_F - P_L)\right]^{0.7} \tag{41}$$

Required instrumentation for a reverse osmosis plant would consist of sensing and automatic data scanning and logging equipment for pressure and flow rate readings and for conductivity measurements on the product water from each module. The estimated capital cost in dollars of this instrumentation is

$$\mathrm{CINST} = 0.2S + 20{,}000\,Q_F^{\;0.7} \tag{42}$$

Because of the large power consumption by a reverse osmosis plant, an electrical substation is provided, whose capital cost in dollars can be estimated from

$$\mathrm{CSUBS} = 850(\mathrm{KW}_N)^{0.7} \tag{43}$$

The capital cost of land acquisition, site improvement, plant housing, and ancillary services and facilities is related directly to plant capacity for modular design and can be estimated in dollars from

$$\mathrm{CSITE} = 0.4S \tag{44}$$

Upon collecting all the cost elements, the total capital cost in dollars of a reverse osmosis plant becomes

$$\mathrm{CCOST} = 3.25S + 224\, Q_F^{\;0.7}\left\{P_F^{\;0.7} + \left[(1-R)(P_F - P_L)\right]^{0.7} + 89.3\right\} + 850\mathrm{KW}_N^{\;0.7} \tag{45}$$

Total annual recurring or operating costs, exclusive of capital amortization which is performed outside the reverse osmosis subroutine, include labor and labor overhead, general supplies and maintenance materials, taxes and insurance, power, and plant remembraning. Estimated annual costs in dollars can be determined by the following expression

$$\mathrm{COSTO} = 0.055\ \mathrm{CCOST} + 61.3\ \mathrm{KW}_N + 1.75S \tag{46}$$

where the first term is comprised of labor and labor overhead, estimated to be equal to 4 percent of capital costs; general supplies and maintenance, equal to 0.5 percent of capital costs; and taxes and insurance, representing 1 percent of total capital costs: the second term is based on a rate of 0.7 cents/kwhr: and the third term comprises the costs for the biennial replacement of membraned tubes at a cost of $3.50/(sq ft) with a useful life of 2 yr.

SUBROUTINE RO

The reverse osmosis subroutine listing is presented in Table 8. A description of variables and their typical values are given in Table 9. Specific wastewater constituent rejections that can be expected are listed in Table 10. The appropriate decision matrix and stream matrix are presented in Tables 11 and 12, respectively.

Table 8

SUBROUTINE RO PROGRAM

```
      SUBROUTINE RO
      DOUBLE PRECISION COMPAR
      DOUBLE PRECISION PRO
      DOUBLE PRECISION PROCSS
      DOUBLE PRECISION IPRO (50)
      INTEGER OS1, OS2
      COMMON /MATRIX/ SMATX(20, 50), DMATX(22, 20), IS1, IS2, OS1, OS2, N
      COMMON /COSTS/ CCOST(20, 5), COSTO(20, 5), ACOST(20, 5),  TCOST(20, 5)
      COMMON /MISC/ PRO(50), COMPAR(20), FRPS(50), URPS(50), GPS(50), APS (50)
     1, DEGC, CAER(50), CAER20(50), DO(50), DOSAT(50), AEFF20(50), URSS(50),
     2XRSS(50), GSS(50), CEDR(50), VAER(50), VNIT(50), MLSS(50), MLASS(50),
     3MLBSS(50), MLNBSS(50), MLDSS(50), AFS(50), FOOD(50), RTURN(50),
     4MLISS(50), CNIT(50), CKWH(50), CFPGAL(50), CAIRP(50), BSIZE(50), TD(50),
     5TDIG(50), C1DIG(50), C2DIG(50), VDIG(50), CH4CFD(50), CO2CFD(50),
     6VFL(50), TVF(50), CFECL3(50), FECL3(50), WP(50), AVF(50), CCHEM(50),
     7TRR(50), GTH(50), GSTH(50), ATHM(50), ERR(50), WRE(50), GE(50), GES(50),
     8AE(50), SBL(50), ASB(50), NN(10), TSMATX(20, 50), ECF(50),
     9BOD2(50), BOD5(50), CCI, AF, CTRP, CTGO, CLAND, TOTCC, TOTTC, TACOST, CCR,
     XTCOSTO, CENG, ECF1, ECF2, ECF3, ECF4, AIRCFD
      REAL MEMB, NETKW, REJ(20)
      NAMELIST /LOCAL/ OFLUX, TOTSA, TOTHL, NETKW
      OREC=DMATX(1, N)
      TOTPR=DMATX(2, N)
      DO 5 K=3, 20
      REJ(K)=DMATX(K, N)
5     CONTINUE
      MEMB=DMATX(21, N)
      ECF(N)= DMATX(22, N)
```

Table 8 (continued)

SUBROUTINE RO PROGRAM

```
      A=1. /(1. 45E-3*MEMB)
      B=TOTPR-(. 01*(1. -(1. -OREC)**(1. -REJ(15))))/(OREC*(1. -REJ(15)))*
     1SMATX(15, IS1)
      C=573.
      OFLUX=(B+SQRT(B*B-4. *A*C))/(2. *A)
      SMATX(2, OS1)=OREC*SMATX(2, IS1)
      SMATX(2, OS2)=(1. -OREC)*SMATX(2, IS1)
      DO 10 K=3, 20
      SMATX(K, OS1)=(1. -(1. -OREC)**(1. -REJ(K)))/OREC*SMATX(K, IS1)
      SMATX(K, OS2)=(1. -OREC)**-REJ(K)*SMATX(K, IS1)
   10 CONTINUE
      TOTHL=1146. /OFLUX
      TOTSA=OREC*SMATX(2, IS1)*1. E6/OFLUX
      NETKW=SMATX(2, IS1)*(. 379*TOTPR-. 212*(1. -OREC)*(TOTPR-TOTHL))
      CCOST=3. 25*TOTSA+224. *SMATX(2, IS1)**. 7*(TOTPR**. 7+((1. -OREC)*
     1(TOTPR-TOTHL))**. 7+89. 3)+850. *NETKW**. 7
```

Table 9

SUBROUTINE RO VARIABLES AND PARAMETERS

Symbol	Typical Value	Description
CCOST	-	Capital cost of plant, \$
COSTO	-	Operating cost, \$/yr
ECF	1.1	Excess capacity factor
MEMB	10. to 25.	Membrane coefficient, μg/(sq cm)(sec)(atm)
NETKW	-	Net pumping requirement, kwhr
OFLUX	-	Average overall plant product water flux, gal/(sq ft)(day)
OREC	.8 to .95	Overall plant product water recovery ratio
REJ(K)	*	Constituent rejections by membrane
TOTHL	-	Total friction energy loss through plant, psig
TOTPR	300. to 800.	Total operating pressure of plant, psig
TOTSA	-	Total membrane surface area of plant, sq ft

---

*See Table 10 for specific rejections.

Table 10

WASTEWATER CONSTITUENT REJECTIONS FOR SUBROUTINE RO

Symbol	Typical Value	Description
REJ(3)	1.00	Solid Organic Carbon
REJ(4)	1.00	Solid Nonbiodegradable Carbon
REJ(5)	1.00	Solid Organic Nitrogen
REJ(6)	1.00	Solid Organic Phosphorus
REJ(7)	1.00	Solid Fixed Matter
REJ(8)	1.00	Solid BOD
REJ(9)	1.00	Volatile Suspended Solids
REJ(10)	1.00	Total Suspended Solids
REJ(11)	0.84	Dissolved Organic Carbon
REJ(12)	0.91	Dissolved Nonbiodegradable Carbon
REJ(13)	0.70	Dissolved Nitrogen
REJ(14)	0.95	Dissolved Phosphorus
REJ(15)	0.89	Dissolved Fixed Matter
REJ(16)	0.89	Alkalinity
REJ(17)	0.88	Dissolved BOD

Table 11

SUBROUTINE RO DECISION MATRIX

DMATX(1, N) = OREC
DMATX(2, N) = TOTPR
DMATX(3, N) = REJ(3), Solid Organic Carbon
DMATX(4, N) = REJ(4), Solid Nonbiodegradable Carbon
DMATX(5, N) = REJ(5), Solid Organic Nitrogen
DMATX(6, N) = REJ(6), Solid Organic Phosphorus
DMATX(7, N) = REJ(7), Solid Fixed Matter
DMATX(8, N) = REJ(8), Solid BOD
DMATX(9, N) = REJ(9), Volatile Suspended Solids
DMATX(10, N) = REJ(10), Total Suspended Solids
DMATX(11, N) = REJ(11), Dissolved Organic Carbon
DMATX(12, N) = REJ(12), Dissolved Nonbiodegradable Carbon
DMATX(13, N) = REJ(13), Dissolved Nitrogen
DMATX(14, N) = REJ(14), Dissolved Phosphorus
DMATX(15, N) = REJ(15), Dissolved Fixed Matter
DMATX(16, N) = REJ(16), Alkalinity
DMATX(17, N) = REJ(17), Dissolved BOD
DMATX(21, N) = MEMB
DMATX(22, N) = ECF

Table 12

SUBROUTINE RO STREAM MATRIX

SMATX(1, IS1)	Feed Water Stream
SMATX(1, OS1)	Product Water Stream
SMATX(1, OS2)	Wastewater Stream
SMATX(2, I)*	Volume Flow, mgd
SMATX(3, I)	Solid Organic Carbon, mg/l
SMATX(4, I)	Solid Nonbiodegradable Carbon, mg/l
SMATX(5, I)	Solid Organic Nitrogen, mg/l
SMATX(6, I)	Solid Organic Phosphorus, mg/l
SMATX(7, I)	Solid Fixed Matter, mg/l
SMATX(8, I)	Solid BOD, mg/l
SMATX(9, I)	Volatile Suspended Solids, mg/l
SMATX(10, I)	Total Suspended Solids, mg/l
SMATX(11, I)	Dissolved Organic Carbon, mg/l
SMATX(12, I)	Dissolved Nonbiodegradable Carbon, mg/l
SMATX(13, I)	Dissolved Nitrogen, mg/l
SMATX(14, I)	Dissolved Phosphorus, mg/l
SMATX(15, I)	Dissolved Fixed Matter, mg/l
SMATX(16, I)	Alkalinity, mg/l
SMATX(17, I)	Dissolved BOD, mg/l

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*I designates stream number, i. e., IS1, OS1, or OS2.

Section VII

ACKNOWLEDGMENTS

The fifteen-month program reported herein was performed by the Environmental Systems Division, Aerojet-General Corporation at El Monte, California, under the direction of Messrs. Gerald Stern and Robert Smith, FWQA Project Officers. Aerojet-General personnel participating in the program were Dr. D. L. Feuerstein, Program Manager; Mr. T. A. Bursztynsky, Project Engineer; Dr. R. W. Lawrence, Project Chemist; Mrs. I. P. Thomason, Analyst; Messrs. B. J. McGrath, A. J. Patak, W. A. Barham, P. A. Tullius, and R. E. Smith, Jr., Laboratory Technicians; Mr. G. K. Haas and Mrs. G. M. Hill, Programmers; and Mrs. M. D. Robinson, Secretary.

The complete cooperation and assistance of the County Sanitation Districts of Orange County, the Orange County Water District, and the County Sanitation Districts of Los Angeles County in providing the municipal wastewaters used in this program is gratefully appreciated and acknowledged.

Section VIII

GLOSSARY

Text Symbols	Computer Symbols	Definition
a		Standard deviation of membrane flux decline coefficient
a_t		Cross-sectional area of individual reverse osmosis tube, sq ft
A	A	Quadratic coefficient
A_o	MEMB	Membrane water permeation coefficient, μg/(sq cm)(sec)(atm)
B	B	Quadratic coefficient
C	C	Quadratic coefficient
$\overline{C}$		Average wastewater solute concentration throughout reverse osmosis plant, mg/l
C_F		Feed water solute concentration, mg/l
C_P		Product water solute concentration, mg/l
C_R		Reject stream solute concentration, mg/l
C_S		Solute concentration, mg/l
CCOST	CCOST	Capital cost of reverse osmosis plant, $
CINST		Capital cost of process instrumentation, $
CMODU		Capital cost of reverse osmosis process modules, $
COSTO	COSTO	Annual operating and maintenance cost of process, $/yr
CPUMP		Capital cost of process high-pressure pumps, $
CSITE		Capital cost of site improvements and housing for process, $
CSUBS		Capital cost of electrical substation for process, $
CTURB		Capital cost for energy recovery turbines for process, $
d		Diameter of individual membraned tube, ft
	ECF	Excess capacity factor
f		Hydraulic friction factor

Text Symbols	Computer Symbols	Definition
f_1		Factor relating laboratory to plant product water quality
g_c		Gravitational constant, $(lb_m)(ft)/(lb_f)(sq\ sec)$
J		Product water flux through membrane, gal/(sq ft)(day)
$\bar{J}$	OFLUX	Average product water flux in process, gal/(sq ft)(day)
J_o		Product water flux on first day at specified concentration condition, gal/(sq ft)-(day)
k		Membrane flux decline coefficient, 1/day
$k_1, \ldots, k_5$		Constants of proportionality
KW		Power consumption for process pumping, kw
KW_N	NETKW	Net power requirement for process pumping, kw
KW_T		Power recovery from process turbines, kw
L_S		Total membraned tube length of series-flow configuration in process, ft
L_T		Total overall membraned tube length in process, ft
N_R		Reynolds number
p		Solute permeation through membrane
P		Net effective pressure causing transport through the membrane, psig
$\bar{P}$		Average net effective pressure in process, psig
P_F	TOTPR	Operating pressure at process inlet, psig
P_L	TOTHL	Total pressure drop of wastewater stream in process, psig
$\bar{P}_L$		Average pressure drop in process, psig
P_O		Osmotic pressure of solution, psig
$\bar{P}_O$		Average osmotic pressure of wastewater stream in process, psig
P_{OF}		Osmotic pressure of feedwater to process, psig

Text Symbols	Computer Symbols	Definition
P_{OR}		Osmotic pressure of reject wastewater from process, psig
Q_F		Feed water flow rate, mgd
Q_P		Product water flow rate, mgd
Q_R		Reject wastewater flow rate, mgd
r	REJ	Solute rejection by membrane
R	OREC	Overall product water recovery ratio of process
s		Specific surface area of individual membraned tube, (sq ft)/ft
S	TOTSA	Total membrane surface area in process, sq ft
t		Time from start of measurement at specified concentration condition, days
T		Absolute temperature, °K
T_F		Turbidity of feed water to process, JTU
TDS_F		Total dissolved solids of feed water to process, mg/l
v_t		Wastewater velocity in individual membraned tube, ft/sec
ρ		Solution density, lb_m/(cu ft)
ν		Solution kinematic viscosity, (sq ft)/sec

1 *Accession Number*	2 *Subject Field & Group*	**SELECTED WATER RESOURCES ABSTRACTS** **INPUT TRANSACTION FORM**

5 *Organization*

Aerojet-General Corporation, El Monte, California

6 *Title*

Reverse Osmosis Renovation of Municipal Wastewater

10 *Author(s)* Feuerstein, D. L. Bursztynsky, T. A.	16 *Project Designation* FWQA Program 17040 EFQ. Contract#14-12-184 21 *Note*

22 *Citation*

23 *Descriptors (Starred First)*

Reverse osmosis, sewage treatment, process model, tertiary treatment, computer model, membrane process, wastewater renovation, demineralization, solids removal, organics removal.

25 *Identifiers (Starred First)*

27 *Abstract*

A fifteen-month laboratory program has shown that all grades of municipal wastewater may be significantly improved by the reverse osmosis process. Comparisons are provided on the behavior and response of the reverse osmosis process to carbon-treated secondary sewage, alum-treated secondary sewage, secondary sewage, primary settled sewage, raw sewage, and digester supernatant. High removals of dissolved minerals, organic substances, and suspended matter have all been achieved in the same treatment. The effects of a flocculant, dispersant, chelating agent, enzyme, and acid on reducing product water flux decline are compared. The relative effects of reverse osmosis test-cell geometry on solids deposition and membrane performance are presented. A phenomenological model is postulated describing the role of undissolved solids and organic substances in producing product water flux decline and the subsequent maintenance of constant product water fluxes. A computer model of the reverse osmosis process, compatible with the executive program written by the Federal Water Quality Administration, has been developed to provide an accurate and rapid method of determining the design and cost of reverse osmosis facilities.

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WR:102 (REV. JULY 1969)
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